THE LIQUID HYDROGEN SYSTEM FOR THE MUCOOL TEST AREA

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ABSTRACT

A new MuCool test area (MTA) is under construction at Fermi National Accelerator Laboratory. This facility will house a cryo-system composed of a liquid hydrogen absorber enclosed in a 5 Tesla magnet. The total volume of liquid hydrogen in the system is 25 liters. Helium gas at 14 K is provided by an in-house refrigerator and will sub-cool the hydrogen system to 17 K. Liquid hydrogen temperature in the absorber is chosen to satisfy the requirement of a density change smaller than +/- 2.5 %. To accommodate this goal and to remove the heat deposited by a beam, a pump will circulate liquid hydrogen at a rate of 450 g/s. The cooling loop was optimized with respect to the heat transport in liquid hydrogen and the pressure drop across the pump. Specific instrumentation will permit an intrinsically safe monitoring and control of the cryo-system. Safety issues are the main driver of the cryo-design.

This paper describes the implementation of the liquid hydrogen system at MTA and the preliminary results of a finite element analysis used to size the LH_2 absorber force-flow.

INTRODUCTION

In the framework of Muon Collider and Neutrino Factory research [1], a Mucool Test Area (MTA) cryo-system is being developed at Fermilab to run components of a cooling cell together under a high power beam test. This experiment will test the feasibility of ionization cooling for an intense ionizing beam passing though a LH_2 energy absorber. Ionization cooling implies that the beam is “cooled” by energy loss and its emittance is reduced; both transverse and longitudinal momentum is lost to collisions with atomic electrons. The beam transversal momentum is damped by ionization energy loss in an energy-absorbing medium like LH_2 and the longitudinal momentum is restored by the RF acceleration between the LH_2 absorbers [2]. Energy loss and Coulomb scattering are in competition in the process of emittance reduction. To maximize the emittance reduction, the smallest atomic number is required. Because of its small atomic number, LH_2 is the best candidate for ionization cooling. Since LH_2 needs to be contained and since any material in between the LH_2 medium and, vacuum provokes undesirable Coulomb scattering effects, a material with a long radiation length is required. Since beryllium has a questionable safety record, then aluminum becomes the optimal material to contain LH_2.

On the basis of the previous requirements, several LH_2 absorbers have been designed. Two potential heat transfer conditions are retained to remove the beam energy deposited in LH_2, while limiting the LH_2 density fluctuations to +/- 2.5 % and preventing LH_2 to reach its boiling point. Heat transfer by force-flow or by convection would satisfy the physical requirements. For both LH_2 absorber types, cold helium is used to maintain LH_2 properties. Although the very first LH_2 test to take place at MTA will consist in the KEK convection type LH_2 absorber, the subject of the current paper focuses on the implementation of the more demanding force-flow cryogenic system. Simulations of the force-flow behavior in the LH_2 absorber with respect to the cryogenic system capacities are introduced in the last section of this paper.

A realistic section to be tested at the MTA is composed of an intense ionizing beam passing though a LH_2 absorber, which is in series with RF cavities and embedded in a magnetic field [1]. The first stage of the cooling-channel components test at MTA will focus on the cryogenic feasibility of LH_2 absorber cooling simulating energy deposition in the forced-flow LH2 absorber with electrical heater.

Hydrogen, nitrogen and helium are the cryogens used for the force-flow LH_2 absorber cryo-system. Parameters of the LH_2 cryo-system are summarized in table 1.

TABLE 1. MTA Cryo-system General Operating Parameters.

Item	Value	Unit
Volume of the LH_2 loop	25	liter
Volume of the vacuum space	26,000	liter
Refrigeration capacity at 20 K	500	W
Refrigeration max mass flow	27	g/s
Refrigeration operating temperature	14	K
Refrigeration operating pressure	0.2	MPa
LH_2 operating temperature	17	K
LH_2 operating pressure	0.12	MPa
LH_2 density	74.28	kg/m^3
H_2 boiling point at 0.12 MPa	21	K
H_2 freezing point at 0.12 MPa	14	K
LH_2 viscosity	3.05	10^{-6} Pa-s
LH_2 specific heat	7696	J/kg-K
Heat of vaporization	445.6	kJ/kg
LH_2 thermal conductibility	97	mW/m-K
Liquid H_2 volume ratio at 20 degree C	790	-

CRYOGENIC FACILITIES

Cryogenic at MuCool Test Area

The MTA cryo-system may be logically divided up into the hydrogen cryo-system and one of the onsite helium refrigeration systems. Figure 1 shows the MTA buildings planned beneficial occupancy for October 2003. MTA is mainly composed of the experimental hall, refrigerator room, compressor room, hydrogen manifold room and service building. The MTA experimental hall is an extension of a new beam line originating from the existing Fermilab 400 MeV proton Linac.

The MTA experimental hall will house the LH_2 absorber cryostat, a superconducting solenoid magnet, superconducting RF cavities, a magnet string and the intense ionizing beam line passing through the experimental hall. The so-called Lab G superconducting solenoid magnet is cooled by LHe and utilizes a LN2 thermal shield. The superconducting solenoid design magnetic field is 5 Tesla.

The compressor room will house two 300 kWatt 2-stage oil injected screw compressors, which supply high-pressure helium gas to the refrigerator room.

Gas helium is supplied by a 34,000 liters helium storage tank located outside the refrigerator room. A complete satellite refrigeration system supplies 14 K helium gas to exchange heat and maintain the 25 liters of LH_2 at nominal conditions. Refrigerator heat exchanger cooling is supplied by a dual cylinder 30 K reciprocating expansion engine. Cold high-pressure helium gas is then expanded through a reciprocating engine to achieve 14 K, 0.22 MPa helium gas to supply the MTA He/LH_2 heat exchanger via a liquid nitrogen shielded transfer line. The nominal 14 K helium mass flow is 30 g/s.

The helium supply is used to cool the hydrogen from room temperature down to below 20 K. During nominal conditions, LH_2 is sub-cooled to 17 K, 0.12 MPa and circulates in a closed loop inside the MTA LH_2 absorber cryostat. The MTA helium refrigeration system can provide up to 500 W of cooling capacity at 14 K to be distributed between the beam load and the system intrinsic loads.

Gaseous hydrogen is distributed from the manifold room to the experimental hall. Three hydrogen gas cylinders are stored in the manifold room but only one bottle will be open at a time for safety reasons. Figure 2 shows the process and instrumentation diagram of the MTA cryo-system and gives an idea of the different flows and interconnections.

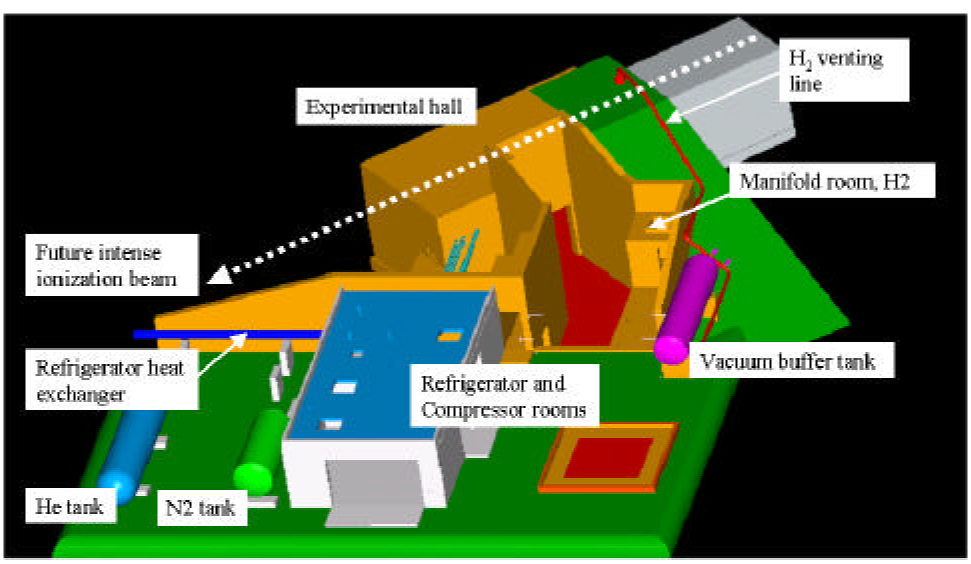

FIGURE 1. MuCool Test Area Buildings 3-D view.

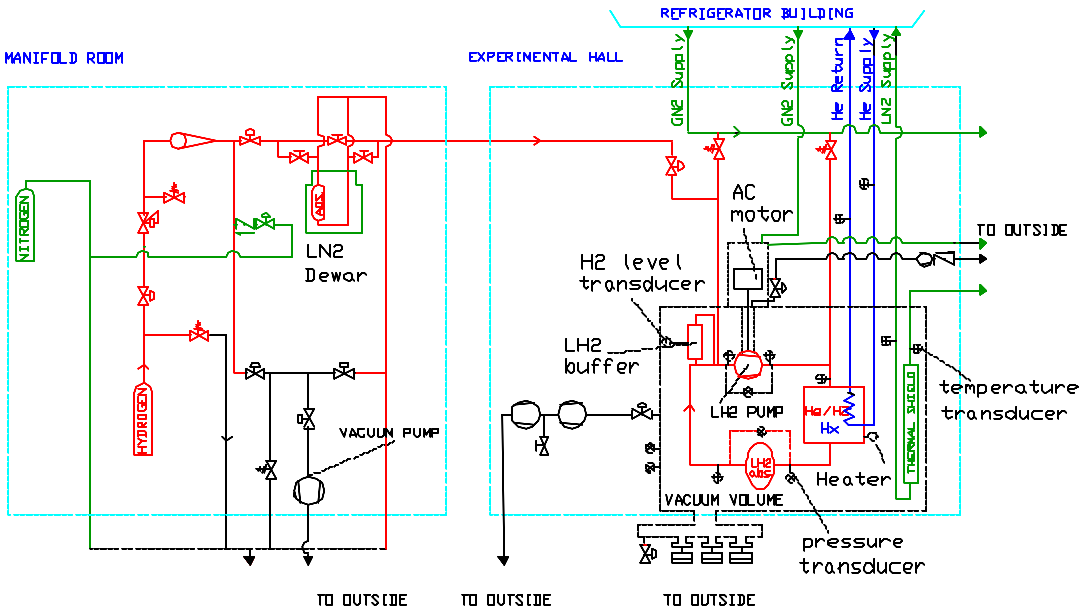

FIGURE 2. Simplified Process and Instrumentation Diagram of MTA cryo-system.

LH_2 Absorber Cryostat

The function of the MTA LH_2 absorber cryostat is to contain the LH_2 loop and to provide the interface with the rest of the cryo-system including the helium, nitrogen and hydrogen transfer lines. The MTA LH_2 absorber cryostat vacuum vessel is mainly composed of a 0.41 m diameter pipe inserted inside the 0.44 m magnet bore and a 1.27 m diameter pipe located outside of the magnet bore. The maximum allowable working pressure (MAWP) of the MTA LH_2 absorber cryostat vacuum vessel is 0.17 MPa. The insulation vacuum is of the order of 1.3×10^{-4} Pa. Figure 3 shows the 3D solid model of the MTA LH_2 absorber cryostat.

Thin aluminum windows close the MTA LH_2 absorber cryostat. As for the LH_2 absorber window, the beam passing through the windows shall interact with a minimum of matter. The shape of these aluminum vacuum windows is similar to the aluminum LH_2 absorber windows.

The MTA LH_2 absorber cryostat thermal shield consists of 4 mm thick aluminum semi-circular shields closed at their edges by G10 supports to reduce forces applied in case of quench of the MuCool superconducting solenoid. Flat sheets protect the non-cylindrical sections of the MTA vacuum vessel. A wrap of 30 layers of MLI surrounds the thermal shield. The MTA cryostat thermal shield is cooled by LN_2 flowing in aluminum cooling pipes.

The supporting systems are composed of G10 material parts supporting the cryostat vacuum vessel, thermal shield, LH_2 absorber and LH_2 pump and piping. G10 material is chosen to limit heat loads from the ambient to the LH_2 loop and to withstand the forces generated during cool down, nominal and quench conditions.

The total volume of the insulation vacuum in which the MTA LH_2 absorber is contained must be 790 times larger than the hydrogen cryo-loop capacity in order to withstand the saturated LH_2 expansion if a rupture of the system should occur. Therefore a 22.4 m^3 vacuum buffer tank is connected to the LH_2 absorber cryostat vacuum vessel to increase the vacuum volume and be in accordance with the safety requirements.

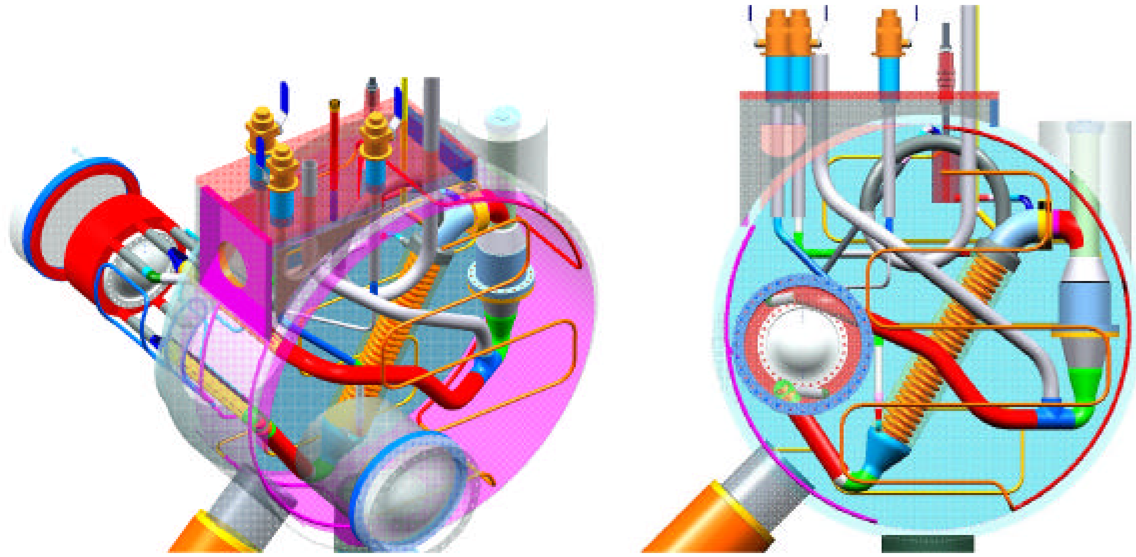

FIGURE 3. 3D Solid Model of MTA Cryostat.

Safety Issues

Safety is the primary concern in designing the MTA cryo-system. The use of hydrogen imposes stringent design, fabrication, installation and operation requirements. The 25 liters in the LH_2 loop have an explosive yield equivalent to about 43 kg of TNT. Careful design and safe handling of hydrogen during the MTA cryo-system operations are a must. The cryo-design provides a safe vent path in the events of a failure in the LH_2 loop or accidental boil-off of hydrogen and is in accordance with ASME, NEC and Fermilab requirements.

Redundant safety features are designed to prevent a hazardous condition when a component fails. Barriers or safeguards are provided to minimize risks and control failures. A safety PLC for process controls and interlock mechanisms named QUADlog® is used. In the case of an emergency, the QUADlog® safety PLC will turn off all vacuum pumps, close appropriate automatic valves, and allow the system to vent. Control valves and control heaters permit to stabilize the cryo-system and especially the LH_2 flow. All electrical devices inside or at the vicinity of MTA LH_2 absorber cryostat must be rated Class I, Division II, group B, or be installed in an intrinsically safe configuration in agreement with NEC safety requirements. Components like capacitance manometers, low excitation current and excess flow valves are used. In addition, N_2 purging for vent lines prevents the mixture of hydrogen gas with the oxygen in air in the presence of an ignition source that could lead to an explosion. Power, and other system services shall be verified for safe performance in the design and normal operational regimes through certification. Oxygen Deficiency Hazard (ODH) detectors are installed in the MTA buildings. Exhaust fans are mounted in the MTA experimental hall and manifold room. No recovery of H_2 is planned. For safety reasons, the venting lines outside of the experimental hall will relieve gaseous hydrogen in an area protected by a fence.

Radiation hard materials are preferred in view of future runs including an intense ionization beam are planned.

Operating procedures for normal and emergency conditions are being written and a special safety committee is reviewing all characteristics of the cryo-system.

LH_2 FORCED-FLOW

LH_2 Circuit

The LH_2 circuit volume is continuously filled with gaseous hydrogen, which is slowly liquefied by helium refrigeration to maintain a constant pressure. The process of filling is slow enough so that the energy generated by transformation from ortho-hydrogen to para-hydrogen is negligible. Gaseous hydrogen is liquefied during cool-down by heat exchange with the cold helium, which is supplied from the refrigerator room at 14 K and heated to 17 K before entering the LH_2 absorber cryostat. When the 25 liters of LH_2 are at nominal conditions (17 K and 0.12 MPa) in the LH_2 absorber, the flow is isolated and the LH_2 pump generates a force-flow able to remove the energy deposited by the beam in the LH_2 absorber.

Instrumentation is installed in the LH_2 absorber and LH_2 circuit to determine temperature profiles, pressure distribution and to measure the flow of LH_2. Operating temperatures and pressure shall permit to stay below the LH_2 boiling point. The LH_2 force-flow design is based on the capacity to remove energy from the LH_2 absorber while keeping a LH_2 density change less than +/-2.5 % and by limiting the loop pressure drop to the capacity available at the LH_2 pump. LH_2 circulates in a closed loop to remove the energy deposited in the LH_2 absorber volume through a counter flow LH_2/He heat exchanger [3]. The 17 K heat load budget distribution for the MTA forced-flow LH_2 absorber test is estimated to be 150 W from the equivalent of the intense ionizing beam passing though a LH_2 absorber, 50 W from the LH_2 pump and 50 W from the ambient to the LH_2 loop. Taking into account additional engineering margin, the heat exchanger is sized for a cooling capacity of 500 W at 17 K. The proposed heat exchanger is a coil made of copper tube. Helium flows inside the copper pipe and LH_2 flows around its tubing. Twenty-seven turns form a coil of 89 mm diameter, which is housed in the heat exchanger outer shell. The 7.6 m long copper tube inner diameter is 15.8 mm, its' wall thickness is 0.8 mm. The heat transfer surface is about 0.34 m^2.

The piping system connecting the LH_2 absorber, LH_2 pump and LH_2/He heat exchanger is composed of stainless steel 25 mm and 50 mm pipe lines. Bimetallic junctions, which are certified to 1×10^{-8} mbar/liter-sec, are used between the aluminum LH_2 absorber and stainless steel piping system. All pipes are welded to limit the risk of hydrogen leaking to the insulation vacuum. The 6.9 liter LH_2 absorber is composed of two thin aluminum windows and one aluminum manifold. Double indium seals are used to seal the two thin windows to the manifold. Holes in the manifold direct LH_2 flow towards the center of the LH_2 window, providing turbulence in the absorber volume to limit the density change.

For the current design the temperature rise is kept within 4 K. The admissible pressure drop through the LH_2 absorber represents about 50% of the total admissible pressure drop in the LH_2 circuit. The total admissible pressure drop in the LH_2 circuit is determined by the LH_2 pump characteristics and the pressure drop across it [4]. For instance, the total admissible pressure drop in the LH_2 circuit shall be less than 2,500 Pa if the LH_2 pump circulates 450 g/s of flow in the LH_2 circuit.

Heat Transfer Numerical Calculations

The design of the LH_2 absorber manifold requires a specific attention. It is important that the thermal power of the beam is removed quickly and efficiently to reduce the risk of hydrogen boiling and thermal stresses in the thin aluminium windows. The temperature must be uniform in the LH_2 absorber to prevent hot spots and LH_2 boiling. The pressure drop of the hydrogen must be kept low enough to meet the pressure drop limits of the LH_2 pump. The main concerns are the LH_2 flow temperature and pressure difference through the LH_2 absorber manifold. The LH_2 absorber manifold hole distribution is of critical importance. For this reason, Computational Fluid Dynamics (CFD) was done to establish the effect of hole orientations and sizes that can achieve the thermal performance targets and still comply with the given design constraints. The CFD software used for this study is the CFX®, which is now part of ANSYS®. The current analysis does not include the metallic window.

Figure 4 shows qualitative views of the numerical analysis whereas Figure 5 shows quantitative results. The CFD model inputs are the 3-D absorber geometry, the beam energy deposition, LH_2 properties, and the velocity of LH_2 at the inlet of the nozzles. The 3σ gaussian distribution beam energy was modeled as a continuous heat source with a uniform spread diameter of 10 mm passing through the LH_2 volume as observable in Figure 4d.

Two models were set up, one without the main inlet chamber as shown in Figure 4a and 4d and one with an inlet chamber. In the model without the inlet chamber, flow is applied directly on each of the 15 inlet nozzles to the absorber, imposing a uniform flow rate on each of them. In the model with the inlet chamber, flow is applied to each of the two main inlets, which has a 25.8 mm bore. This latter case may not result in a uniform flow rate at each of the 15 inlet nozzles to the absorber. The ratio of the flow rate at the main inlet at the chamber to the individual inlets to the absorber is approximately 2.2 : 1.

Several nozzle distributions were studied for each model and in particular for the one with the velocity applied to the chamber inlet. Configuration A represents 11 inlet and 15 outlet nozzles, configuration B represents 15 inlet and 19 outlet nozzles. Figures 4b, 4c, 4e and 4f show a qualitative appreciation of the temperature and velocity distributions. The results of this numerical analysis underlines that inlet nozzles distribution must be 15symmetric to allow smaller temperature rise and hence the maximum removable energy.

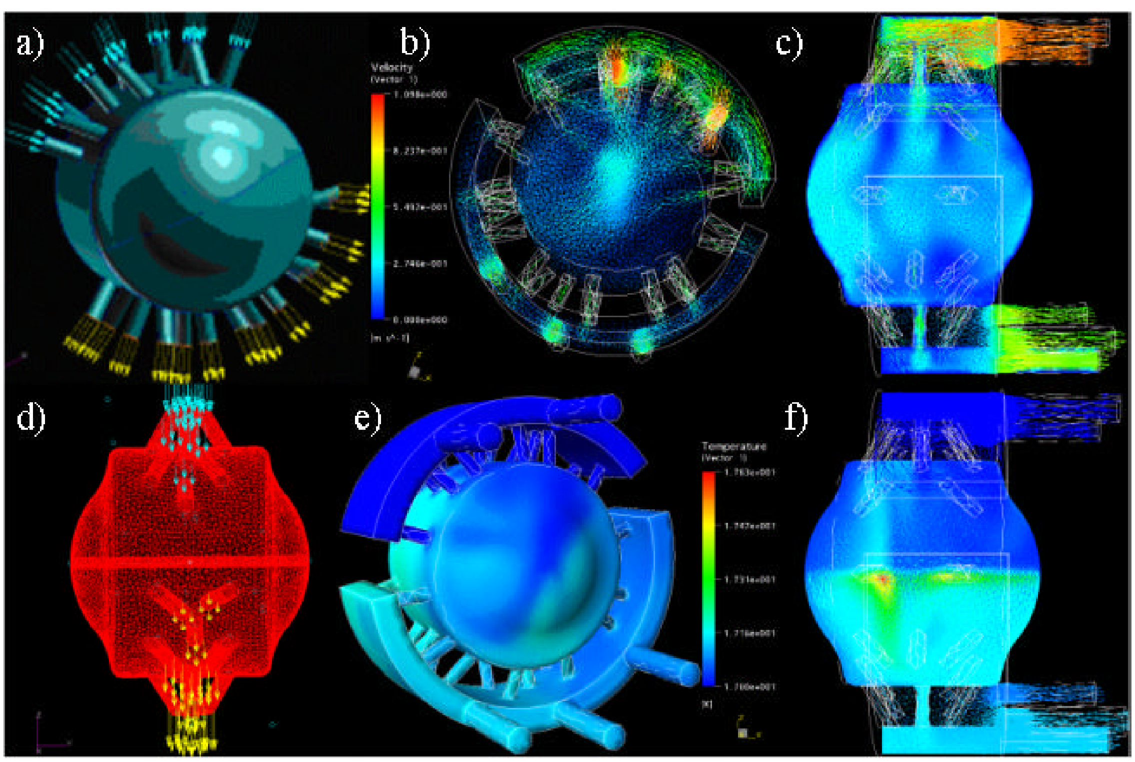

FIGURE 4. Configuration B with 300 W of beam power, v=4 m/s; a) CFD model with flow direction; b) velocity distribution - front view; c) velocity distribution - side view; d) meshing with beam; e) temperature distribution and inner chamber visible; f) temperature distribution - side view.

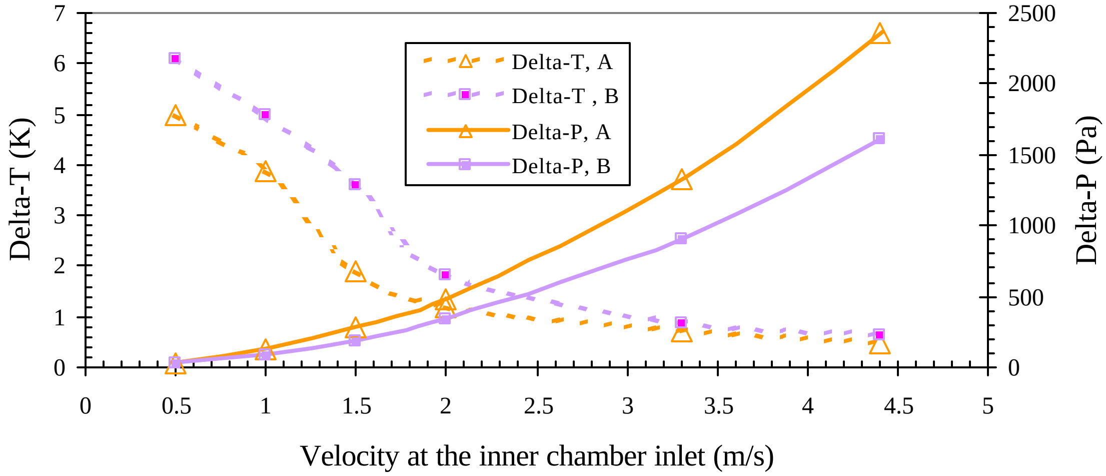

FIGURE 5. Influence of the velocity for configurations A and B. Delta-T is the maximum temperature difference obtained in the LH2 absorber, Delta-P is the pressure drop between inner chamber inlet and outlet.

Figure 5 shows the influence of the velocity for these two symmetrical distribution configurations and shows that the use of more nozzles is not favorable to a temperature decrease but does limit pressure drop. Since the pressure drop in the system is the parameter of importance, 15 inlet and 19 outlet nozzles with a mass flow around 160 g/s is a good compromise.

CONCLUSION

The first components of the MuCool cooling channel, the LH_2 absorber will start to be tested in October 2003. The cryo-system is designed to be in compliance with safety codes. CFD results permit to address the LH_2 force flow design and permit to understand the interdependence between the LH_2 flow characteristics.

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