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A THIN GOLD COATED HYDROGEN HEAT PIPE -CRYOGENIC TARGET FOR EXTERNAL EXPERIMENTS AT COSY

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Abstract

A gravity assisted Gold Coated Heat Pipe (GCHP) with 5-mm diameter has been developed and tested to cool a liquid hydrogen target for external beam experiments at COSY. The need for a narrow target diameter leads us to study the effect of reducing the heat pipe diameter to 5mm instead of 7mm, to study the effect of coating the external surface of the heat pipe by a polished gold layer (to decrease the radiation heat load), and to study the effect of using the heat pipe without using 20 layers super isolation around it (aluminized Mylar foil) to keep the target diameter as small as possible. The developed gold coated heat pipe was tested with 20 layers of super isolation and without. The operating characteristics for both conditions were compared to show the advantages and disadvantages.

Keywords: Target/; Cryogenics/ Low temperature equipment/ Heat pipes.

INTRODUCTION

Nuclear reactions take place between accelerated particles and target materials. At the COoler SYnchrotron (COSY) interactions of protons in the GeV energy range with target nuclei are studied. The target materials in our experiments are liquefied hydrogen and deuterium. To liquefy them, a standard cooling machine (RGD 210 Leybold AG) is used (1) and the target is built on the 2nd stage of this cooling machine as shown in figure (1). Earlier target versions used different heat conductors between the cooling machine and the target region (2). The longer and narrower heat link between the target and the cooler is needed for two reasons. Firstly, the cooler has to be as far as possible from the reaction point to avoid secondary interactions. Secondly, shadowing of the measuring detectors needs to be avoided. The shortest cooling down and heating up times were obtained with aluminum (the best heat conductor). A large improvement has been achieved by changing from metallic conduction to heat transfer by convection in heat pipes. Evaporation and condensation of a working fluid at opposite ends of a tube is used to transfer a large amount of heat (3-6). A 16 mm diameter heat pipe was developed and tested (7). Other improvements in the target performance were achieved by using aluminum instead of copper as the condenser and a 7mm-diameter heat pipe instead of 16mm (8). Further development is using a gold coated aluminum heat shield around the cold parts of the cold head and a 5 mm gold coated heat pipe (9). After the success of these developments and due to the

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need for narrower diameter targets the question was raised what is the lower limit of the target which still allows stable operation? To answer this question, a gold coated heat pipe with 5 mm diameter was designed and built without super isolation and heat shield. The internal plastic tube for the liquid flow from the condenser to the evaporator was kept at the same diameter of 3mm. The reduction in the heat pipe diameter only affects on the cross sectional area of the vapor flow from the evaporator to the condenser (12.56 mm^2 instead of 31.4 mm^2 for the 7mm diameter heat pipe).

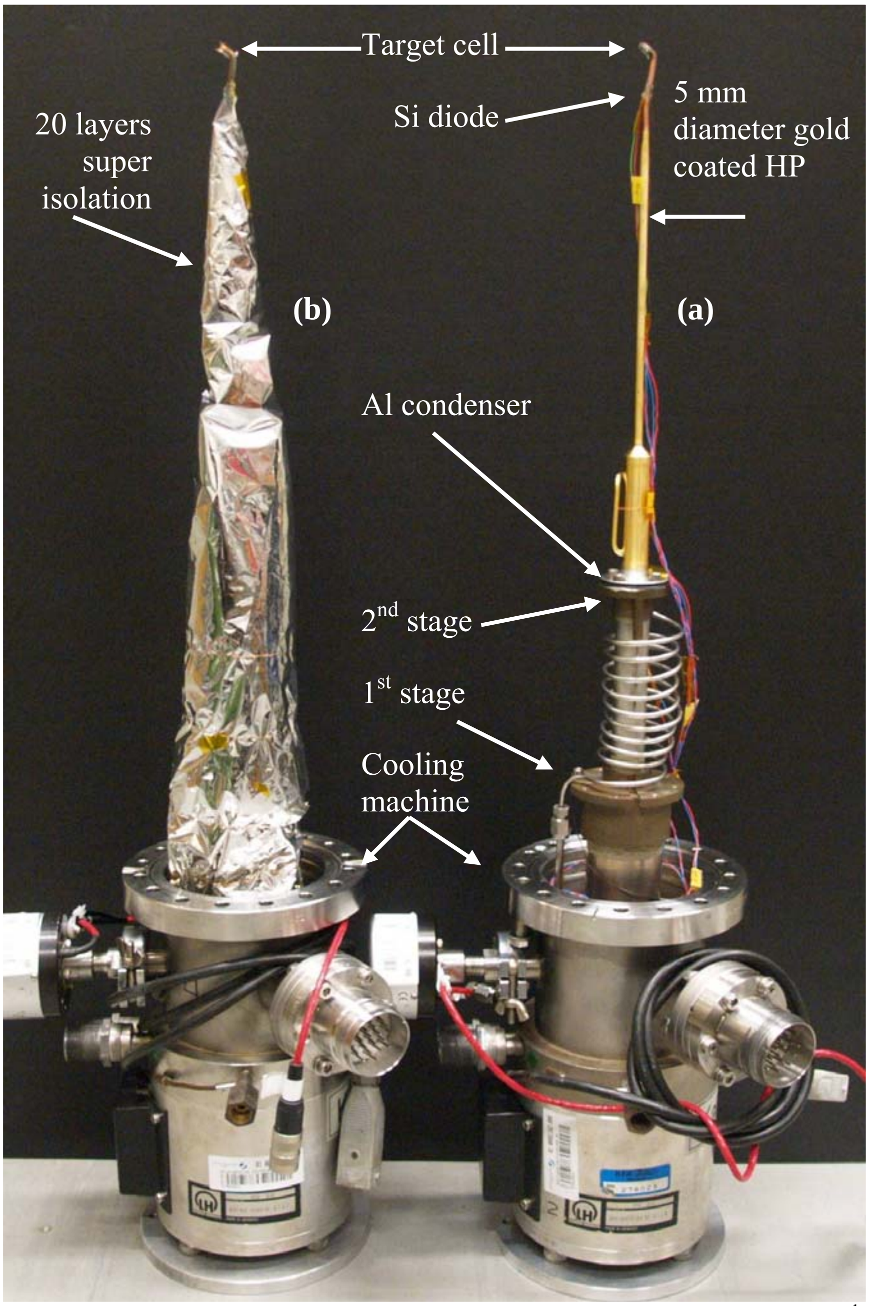

Fig. (1): Standard cooling machine RGD 210 Leybold AG with target built on the 2nd stage, (a) 5mm diameter gold coated heat pipe target, (b) 5mm diameter gold coated heat pipe target with 20 layers super isolation.

The target liquid material is contained in a cylindrically shaped thin copper cell (wall thickness 30 µm) with 6mm diameter and 4 mm length fabricated by galvanization. The beam entrance and exit apertures are closed by using 0.9 µm Mylar foil [2]. The hydrogen gas inside the heat pipe system has a pressure of 205 mbar at room temperature (filling pressure to have enough amount of liquid). This low pressure must be stabilized during the operation to higher and stable values than the hydrogen triple point (70 mbar, 13.9 K) to prevent the formation of solid hydrogen that stops the heat pipe operation. A pressure stabilization system [11] is used for that purpose.

The study in this paper will concentrate on measuring the 5mm diameter gold coated liquid hydrogen heat pipe characteristics in two cases:

1. Heat pipe isolated with 20 layers aluminized Mylar foil (with super isolation).
2. Heat pipe without isolation by aluminized Mylar foil (without super isolation).

The measurements were done at 40° inclination with respect to the horizontal plane.

For both conditions, the cool down time for hydrogen has been measured (section 3). The temperature difference between the condenser and the evaporator of the heat pipe has been measured and compared (section 4). The effective thermal conductivity (section 5), the liquid hydrogen mass (section 6), a comparison between the 16 mm, the 7 mm, and the 5 mm diameter heat pipes (section 7) have been done.

HEAT PIPE DIMENSIONS AND DESIGN

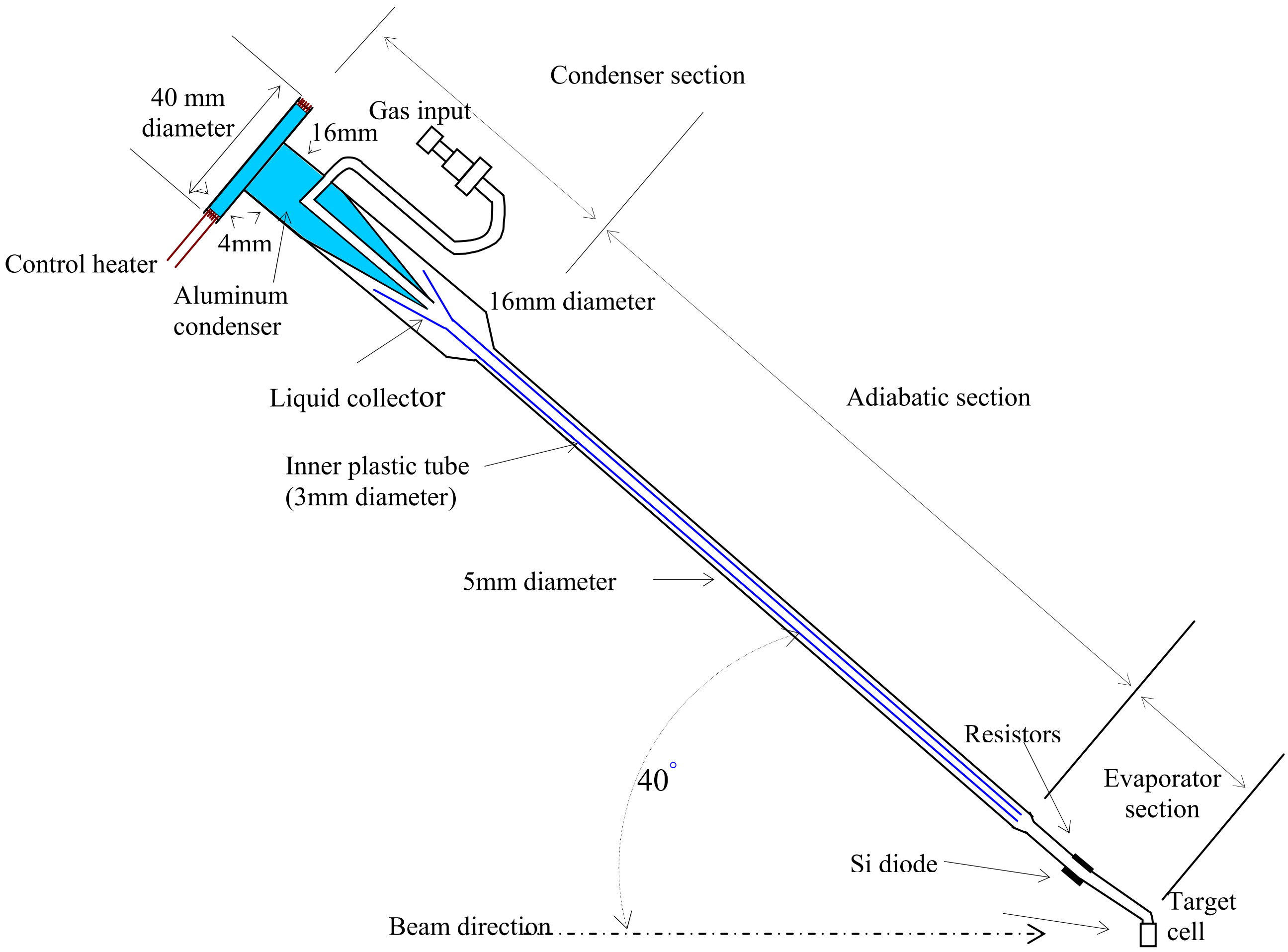

Fig. (2): Schematic diagram for the condenser- 5mm gold coated heat pipe-target combination

A gold coated (≈0.1 µm polished gold layer) -5mm diameter-32cm long heat pipe with 0.1mm wall thickness from stainless steel was developed. The material, the surface area, the thermal heat radiation, and the heat capacity have been reduced compared to the previously used 16 mm and 7mm diameter heat pipes. An aluminum condenser with a control heater around it was used in the upper part. Also a gold coated target appendix with very thin copper walls (30 µm, made by galvanization) was used in the lower part as the evaporator. Attached to the target appendix is a small resistor (160Ω) to allow a heat load in addition to thermal radiation to be applied to the target (applied heat load). A 3-mm diameter plastic tube with 0.1 mm wall thickness was used in the center of the heat pipe for liquid transportation between the condenser and the evaporator and it is identical to the one used for the 16 mm and 7 mm heat pipes. Figure (2) shows a schematic diagram of the heat pipe with the target appendix, the internal tube, and the aluminum condenser. Table (1) summarizes the parameters of this developed target version.

Table (1): Parameters of the 5-mm diameter gold coated heat pipe with an aluminum condenser.

Total heat pipe length	**320**	**mm**
Part with 16 mm diameter (condenser)	**70**	**mm**
Part with 5 mm diameter (adiabatic)	**200**	**mm**
Evaporator part	**50**	**mm**
Wall thickness	**0.1**	**mm**
Inner tube length	**200**	**mm**
Outer diameter	**3.2**	**mm**
Wall thickness	**0.1**	**mm**
Weight of evaporator	**0.735**	**g**
Weight of inner tube	**0.385**	**g**
Weight of HP without gas connector	**6.080**	**g**
Weight of gas connector	**5.440**	**g**
Weight of Al condenser	**22.540**	**g**
The total weight	**35.180**	**g**

COOL DOWN TIME WITH LH_2

Hydrogen is used as the fluid material in the heat pipe and at the same time as the target material. The cool down time to have LH_2 in the target cell has been measured with the gold coated heat pipe covered with super isolation and free from super isolation (without super isolation). The difference between the cool down times is 4 minutes. The time dependence of the condenser and evaporator temperatures with and without super isolation at the filling condition (205 mbar, 6.13 liter) is shown in Figure (3). The condensation of hydrogen around the aluminum condenser started 39 minutes after switching on the cooling machine. The total cool down time from starting the cooling until the LH_2 reaches the target cell is 44 and 48 minutes with and without super isolation, respectively. Thus, 5 and 9 minutes respectively are required for the liquid to proceed down and reach the evaporator section. During that time the liquid must cool down the internal plastic tube over its full length. Afterwards, 0.54 cm^3 of LH_2 is present in the system. Thereafter, only a couple seconds are needed to fill the target cell with LH_2. Finally, the system has a steady rate of condensation on the condenser and flow of liquid down in the inner tube, vaporization in the evaporator and flow of vapor upwards in the space between the 3mm diameter inner tube and the 5mm diameter heat pipe. The cool down time without using super isolation is longer because of the thermal radiation from the surroundings. This can be estimated from black body radiation formula

$$P = \sigma A \varepsilon (T_{outside}^{4} - T_{surface}^{4}), \quad (1)$$

Where σ is the Stefan-Boltzmann constant = (5.7×10^{-8} W m^{-2} K^{-4}), A is the surface area of the 5mm heat pipe (7.4 E-3 m^2), ε is the emissivity of the surface (polished gold = *0.018*), $T_{surface.}$=15 K, $T_{outside}$ =300 K.

From that the thermal radiation power to the polished gold coated 5mm heat pipe target system is 61.0 mW and for the polished gold coated 5mm heat pipe with super isolation target system is 15.0 mW. So the liquid takes longer to reach the target cell. In both cases the heat pipes work with the applied heat loads.

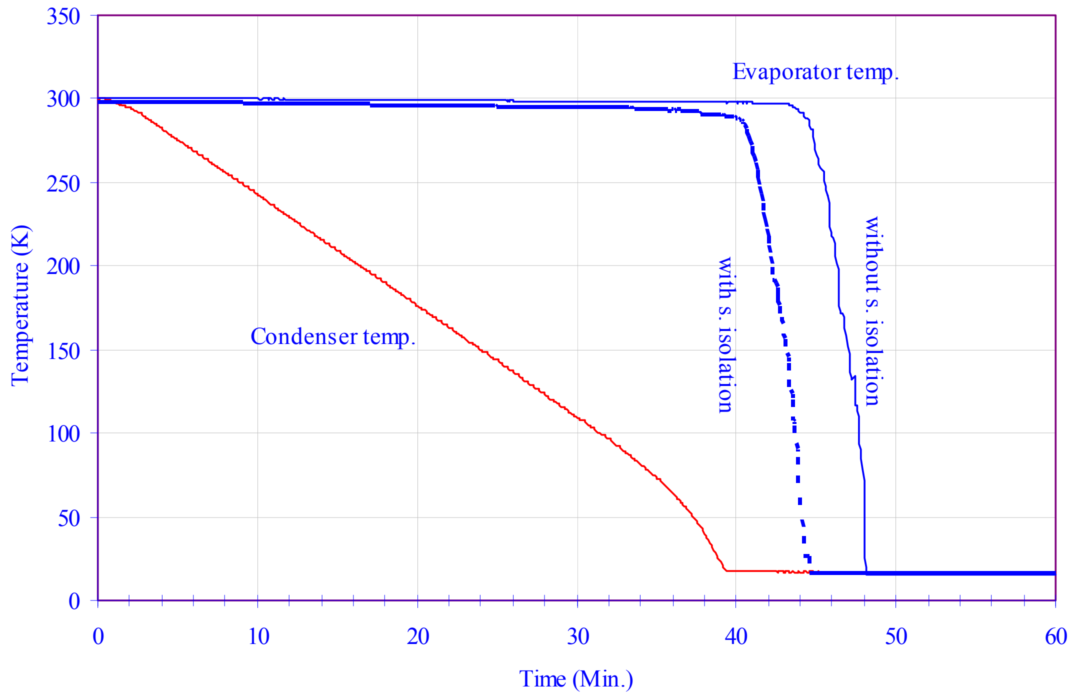

Fig. (3): Time dependence of the condenser and evaporator temperatures for LH_2 for 5mm diameter gold coated heat pipe with and without super isolation.

TEMPERATURE DIFFERENCE BETWEEN THE ENDS OF THE HEAT PIPE

The temperature difference ΔT between the external surface of the evaporator and the external surface of the condenser of the heat pipe–target system is measured as a function of the applied heat load on the evaporator at different condenser temperatures. A small ΔT allows us to operate the cold head at a higher temperature where higher cooling power is available [(10)]. Figure (4) shows the measured ΔT for different applied heat loads at the evaporator for different condenser temperatures in steady-state operating conditions with and without super isolation. ΔT increases with increasing the applied heat load at the same condenser temperature, increases with increasing condenser temperature for the same applied heat load (due to the reduction of the heat pipe thermal conductivity), and increases without using super isolation at the same condenser temperature and applied heat load (due to the increased radiation heat load on the heat pipe).

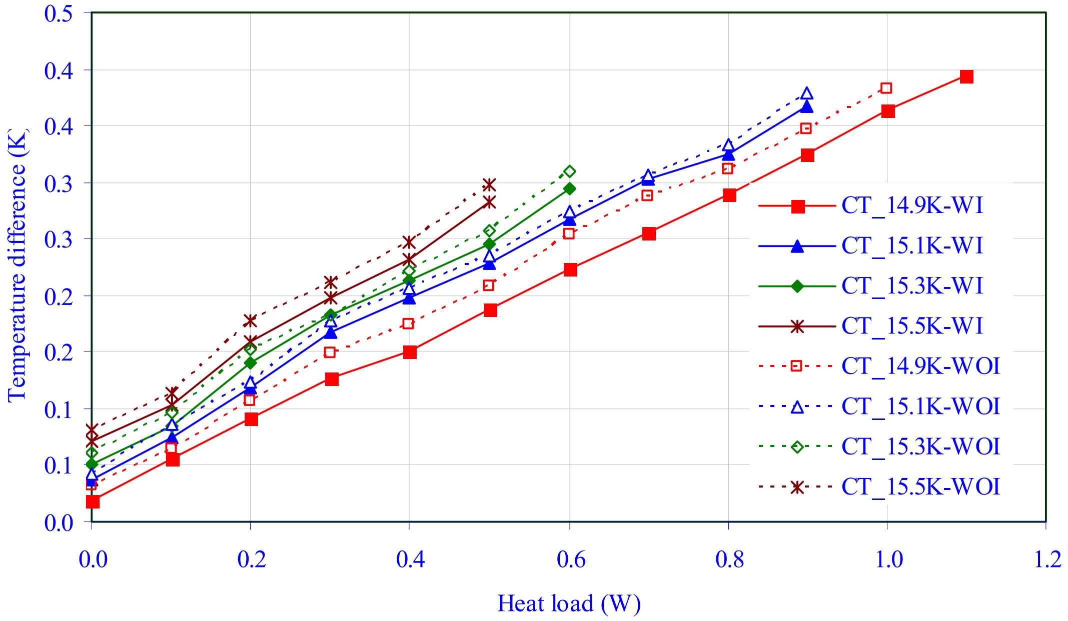

Fig. (4): Temperature differences between the condenser and the evaporator of the hydrogen gold coated heat pipe versus the applied heat loads at the evaporator for different condenser temperatures with (solid curves) and without (dashed lines) the super isolation.

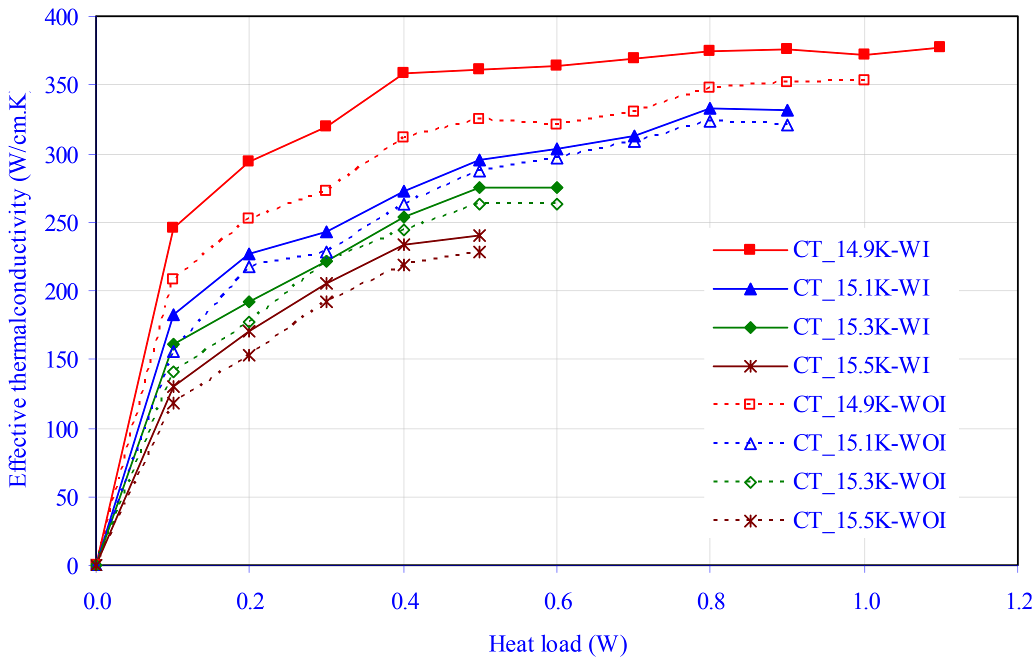

Fig. (5): Effect of applied heat load on K_{eff} for the hydrogen 5mm diameter gold coated heat pipe target system for different condenser temperatures with (solid curves) and without (dashed lines) the super isolation.

When the applied heat load on the evaporator exceeds a certain maximum value the LH_2 will evaporate completely from the evaporator and its temperature will increase. The ΔT ranges from 0.018 to 0.395K with using super isolation and from 0.032K to 0.383 K without using super isolation depending on the condenser temperature and the applied heat load. The heat pipe system can transfer up to 1.1W applied heat loads with the super isolation compared to 1.7 W applied heat load for the 7mm diameter heat pipe with super isolation and without gold coating. The 5mm diameter gold coated heat pipe ceases to operate at 1.1 W heat load although it still has enough liquid quantity inside. This is because there is only 40% of the cross sectional area for vapor flow compared to the 7 mm heat pipe. The correspondingly much faster flow of vapor upwards hinders the liquid flow downward to the evaporator.

EFFECTIVE THERMAL CONDUCTIVITY OF THE HEAT PIPE

The effective thermal conductivity (K_{eff}) gives an indication of the additional heat flow rate resulting from the applied heat load. High values are required for a stable working target. The K_{eff} for the heat pipe system [12-14] is determined by the following equation:

$$K_{eff} = \frac{L \cdot \dot{Q}}{\Delta T \cdot A} , \qquad (2)$$

where $\dot{Q}$ is the heat transfer rate, ΔT is the temperature difference between evaporator (T_2) and condenser (T_1), L is the distance between the measuring points of T_1 and T_2 and A is the cross-sectional area of the heat pipe. Figure (5) shows the effective thermal conductivity K_{eff} of the hydrogen heat pipe-target system as a function of the applied heat load for different condenser temperatures with super isolation (WI) and without (WOI). The results show that K_{eff} increases with increasing the applied heat load, with decreasing the condenser temperature and with using super isolation around the heat pipe at the same applied heat load and condenser temperature. The K_{eff} decreases with increasing the condenser temperature because of the increase in condenser temperature decreases the condensation rate of liquid which leads to an increase in the temperature difference ΔT and then decrease in the K_{eff}. The highest measured thermal conductivity with super isolation is 376.5 W/cm·K compared with 353 W/cm·K without using super isolation.

LIQUID MASS IN THE HEAT PIPE-TARGET SYSTEM

The heat pipe working fluid is the target material used for the nuclear reactions (liquid hydrogen). The target system should have sufficient liquid for proper operation of the heat pipe and complete filling of the target cell. The gas filling in the heat pipe system is (1.24 l·atm). For the target and heat pipe operation a fraction of the available gas is converted into liquid. The change in the gas content is determined by the changes in the volume of the bellow ΔV and the pressure [10]. The mass of vapor removed from the bellow ($m_{\Delta v} = \Delta V \cdot \rho_{gas(295K, P)}$) is converted into the mass of cold gas in the heat pipe ($m_{cg} = V_{HP} \cdot \rho_{cg\ (200\ mbar,\ sat)}$) and the liquid mass in the system ($m_l = m_{\Delta v} - m_{cg}$), where V_{HP} is the volume of the heat pipe and m_l is the mass of liquid in the heat pipe target system. The subscripts *p, cg*, *sat*, v, *l*, HP indicate pressure, cold gas, saturation, vapor, liquid and heat pipe, respectively.

In the 32 cm long target system some liquid is needed above the evaporator. Due to the condensation of the hydrogen around the condenser and the flow of the liquid in the inner plastic tube, part of the liquid adheres to the surface of the condenser and the inner tube (0.54 cm^3). The quantity required in the target cell and appendix is nearly equal to that value (it is 0.5 cm^3 which corresponds to 38 mg LH_2). Figure (6) shows the amount of liquid H_2 in milligrams inside the 5 mm diameter heat pipe target system at various condenser temperatures and applied heat loads. The liquid mass decreases with increasing condenser temperature and increasing applied heat load on the evaporator due to the decrease in condensation rate in the condenser section and the increase in vaporization in the evaporator (target). The 5 mm diameter gold coated heat pipe operation stops even though there is enough liquid (dotted line in figure (6)) inside it. The reason why the heat pipe ceases to operate is that the high speed of the vapor proceeding upward (64 cm/s) prevents the liquid from flowing downward in the inner plastic tube.

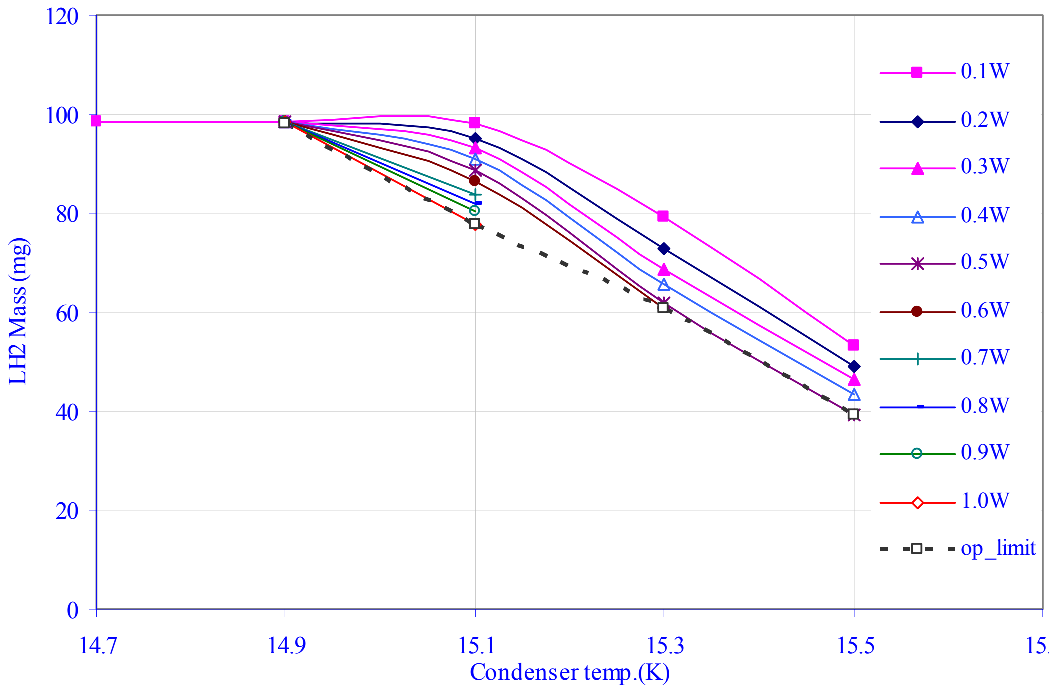

Fig. (6): Mass of liquid hydrogen inside the 5 mm gold coated heat pipe target system versus the condenser temperature at different applied heat loads and the heat pipe operation limits (dashed curve).

COMPARISON

The comparison between the 16 mm, 7 mm, and 5 mm diameter heat pipe aims to show the advantages and disadvantages of them. This comparison allows further optimization of the heat pipe depending on the following parameters:

- The weight of the heat pipe should be minimized in order to decrease the background reactions.
- The cool down time should be as short as possible in order to optimally use the very expensive COSY beam time.
- The target average external diameter should be as small as possible in order to decrease the space used within the detector system and thus decrease the shadowing.
- The thermal conductivity should be as high as possible in order to increase the sensitivity and the response to the changes in the heat loads.
- The maximum temperature difference between the condenser and evaporator should be as small as possible in order to allow the cooling machine to work at higher condenser temperature and thus provides more cooling power [10].
- The heat pipe surface area should be as small as possible in order to decrease the radiation heat load which is directly proportional to the surface area of the heat pipe.

Table (2) summarizes the parameters of the heat pipes. From the table, one can select the heat pipe diameter depending on the used detector system and the type of measurements (liquid or gas target measurements).

Table (2): Comparison between the 16mm, 7mm, and 5-mm diameter heat pipes with an aluminum condenser.

	16 mm diameter heat pipe with super isolation	**7 mm diameter heat pipe with super isolation**	**5 mm diameter gold coated heat pipe**	
			without super isolation	**with super isolation**
Weight with Al condenser (g)	**41.5**	**36.7**	**35.1**	**35.1**
Cool down time (minutes)	**57**	**47**	**48**	**44**
Maximum K_{eff} (W/cm·K)	**80**	**422**	**353**	**377**
Maximum temp. difference (K)	**0.27**	**0.24**	**0.383**	**0.395**
Heat pipe surface area (cm^2)	**133.2**	**77**	**66.5**	**66.5**
Maximum heat load (W)	**1.0**	**1.4**	**1.0**	**1.1**
Average external target diameter (mm)	**40**	**35**	**5**	**30**
Maximum vapor speed (cm/s)	**3.7**	**32.3**	**57.3**	**63.7**

CONCLUSION

In this study a 32 cm long stainless steel-gold coated heat pipe with 5mm diameter has been developed. The heat pipe was tested with hydrogen gas with and without super isolation. The heat pipe operation was successful without super isolation around it which is a good advantage to decrease the shadowing effect for the detectors and background measurements. As advantages the 5 mm heat pipe has,

- Low mass: that means it has a lower heat capacity, shorter cool down time and generates less background.
- Small surface area: that means it is exposed to a lower radiation heat load from the surroundings.

- Small diameter: that means it makes lower detector shadowing and needs less volume in the detector system.
- The cool down times were 44 and 48 minutes with and without super isolation, respectively. The maximum effective thermal conductivities were (376.5, 353W/cm·K), the maximum temperature difference between the condenser and evaporator were (0.395, 0.383 K), the vapor flow velocities were (63.6, 57.3cm/s), and works with maximum applied heat loads up to 1.1W and 1.0W with and without super isolation, respectively. Although the 5mm diameter gold coated heat pipe has those advantages, it is not the optimal diameter because the small cross sectional area used for the vapor flow upward which results in a high vapor velocity. This resists the liquid from flowing downward in the inner plastic tube. As a result, the heat pipe stops to operate even though there is still enough liquid inside it. Furthermore, there is a high temperature differences between the condenser and evaporator which requires the cooling machine to work at lower condenser temperatures where there is lower cooling power.

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