DESIGN OF LIQUID NITROGEN CRYOSORPTION PUMP

[1] *MR. M.B.PRAJAPATI,* [2] *DR. S.M.MEHTA*

[1]M.E. [Cryogenics] Student, Department Of Mechanical Engineering, L D College Of Engineering, Ahmedabad, Gujarat
[2] Professor, Department Of Mechanical Engineering, L D College Of Engineering, Ahmedabad, Gujarat

milapn.prajapati@gmail.com, shreya74@gmail.com

***ABSTRACT*: *Cryopumps make use of a cold surface to adsorb gas molecules. They are usually classed into two families, depending whether they rely on the binding forces between gas molecules and solid surfaces (cryosorption pumps) or on the even weaker forces which bind condensed gas molecules together (condensation pumps).cryopump have certain advantages like high speed for water vapour, high throughput, very clean and contamination free vacuum, low operating costs, choice of orientation and rotary pumps required to rough out. Due to the temperature difference there is always heat in leak into the vacuum chamber from the atmosphere. The cryopump for cylindrical vessel to be developed and LN_2 is used as cryogen in the pump. Charcoal is selected as sorption material. The parameters like pumping speed, throughput, ultimate pressure, pumping capacity and regeneration time to be measured.*

Keywords—Cryosorption pump, vacuum, cryopanel, LN_2, Sorption material

I: INTRODUCTION

The Vacuum technological design of a cryopump aims to maximize the pumping speed S within the usual parameter such as temperature T, the surface area of cryopanel, and the properties of the gas being pumped.

The proposed system consists of two concentric cylinders. The outer cylinder works as vacuum vessel and inner cylinder as cryopanel. The inner cylinder which works as cryopanel is to be cooled by liquid nitrogen. The space between two cylinders is to be evacuated by available conventional pumping system consisting of mechanical rotary pump. Design of cryosorption pump includes Estimation of size of cryopanel required for condensation and cryosorption. The size of cryopanel required for pumping speed of 1000 l/s and ultimate pressure of 10^{-4}Pa will be calculated.

II: OPERATING PARAMETER

There is a set of parameters to characterize the performance of cryosorption pumps. They are listed and discussed in the following section.

Pumping speed:-The pumping speed is the central scaling criterion for a cryopump and defined as the quotient of the throughput Q of a gas and the working pressure p.

$$S = \frac{Q}{P}$$

This equation holds, as long as the ultimate pressure of the pump is negligible against the working pressure, which is usually the case. It is equivalent to a volume rate of flow and is expressed in l/s, referenced to T = 273.15K. To convert to number of existing cooling supply condition and space limitation. The basic design eq. (3.3.1) shows that

particle or amount of substance based units, the ideal gas law can be used:

$$P \times V = n\,RT$$

where V denotes the volume of the vacuum chamber, n the number of moles of gas present, and R the universal gas constant R = 8.3145J/(molK). The pumping speed for the present experiment is selected 1000 l/s.[1]

Maximum throughput:-This is the maximum constant gas flow rate which can be pumped by a cryopump at temperatures at 80K in the second stage. The throughput is usually expressed in (Pam^3)/s, taken at T.

Pumping capacity:-The pumping speed decreases with an increasing amount of pumped gas. For adsorbed gases in particular, the pumping speed asymptotically reaches zero. The pumping capacity is defined as the quantity of gas that has been pumped until pumping speed has been reduced to 50% of the initial value. The capacity is expressed in (Pam^3).

Ultimate pressure:-This is defined as the lowest pressure achieved by vacuum pump is called ultimate pressure. The ultimate pressure for the present Cryosorption pump will be 10^{-4}Pa

Cool-down time:-This denotes the elapsed time between turning on the refrigerator of a cryopump at room temperature and achieving temperatures of 80K.[2]

III: MATERIAL SEECTION

The material(s) of construction is required to provide as little gas load as possible while still being strong enough to withstand the forces exerted by the external atmospheric pressure. The strength issue is easily dealt with by making the walls thick enough or by adding additional bracing or supports either internally or externally, but the main problem is found in assessing the possible gas loads. The gas load due to outgassing for different matrial are as below.

Vacuum material	Outgassing Rate(Pa liters/Sec/m^2)
SS304	8.0×10^{-11}
Aluminium	9.0×10^{-11}
Mild Steel	7.0×10^{-8}
Brass	6.0×10^{-8}
High density Ceramics	5.0×10^{-11}
Pyrex	1.0×10^{-10}

Table 1 Outgassing rate of different vacuum material.

Metals are the most prevalent vacuum chamber materials, with stainless steel far ahead of other metals such as mild steel or aluminum alloys. It would seem that a choice between SS or Al would be sufficient, but this is only the beginning of the selection process. For example, deciding to use SS doesn't mean any and all SS alloys. Free-machining alloys such as 303 SS contain sulfur, but the vapor pressure of the S is too high for high vacuum systems. 304SS, though, is the most common choice. This helps narrow things down, but ultrahigh vacuum usually requires the low-carbon 304L alloy.

For the prsent work SS304L is selected for all metal work.

V: DIENSIONS OF CRYOPANEL

The cryopump consist of cryopanels as pumping surfaces. The pumping surfaces or the cryopanels can be arranged circularly and suspended from the header. The required pumping speed 1000l/s and ultimate pressure is 10^{-4}Pa. The size of cryopanel will be determined with the help of given equation, As in [3]

$$S_{th} = A_k \cdot S_a \cdot \alpha \cdot \left(1 - \frac{P_u}{P}\right)$$

Where,

S_{th}= pumping speed,

A_k= Size of the cryopanels,

α =Probability of condensation (pumping),

S_a =Surface area related pumping speed,

P_u =Ultimate pressure (see above),

P = Pressure in the vacuum chamber.

The surface area related pumping speed Sa is given by, As in [3]

$$S_a = \sqrt{\frac{R \cdot T_g}{2 \cdot \pi \cdot M}}$$

$$= 3.65\sqrt{\frac{T_g}{M}} \ \text{l/s cm}^2$$

Where,

T_g=Gas temperature in K,

M=Molar mass (for air 28.96 gm/mol)

So that surface area related to pumping speed is,

$$S_a = 3.65\sqrt{\frac{300}{28.96}}$$

$= 11.7477$ l/s cm^2

Now the surface area of the cryopanel is calculated as below,

$$S_{th} = A_k \cdot S_a \cdot \alpha \cdot \left(1 - \frac{P_u}{P}\right)$$

$$1000 = A_k \cdot 11.74 \cdot 0.062 \cdot \left(1 - \frac{10^{-4}}{10^{-1}}\right)$$

$$A_k = 1375.22\text{cm}^2$$

Here the inside cylinder works as cryopanel. The diameter (D_1) and length (L_1) of the inside cylinder is selected as 160mm and 180mm respectively. The diameter ($D_2=D_1+2X_1$) and length ($L_2=L+L_1+2X_1$) of outside cylinder is selected as 210mm and 320mm. So the size of vacuum chamber created is 200mm by 100mm. The inlet pipe diameter D and length L for supplying cryogen to inside cylinder is selected 22mm and 105mm in vessel.

According to the ASME code, Section VIII, the minimum thickness of the inner cylindrical vessel is determined as below,

$$t_1 = \frac{pD_1}{2S_ae + 0.8p}$$

Where,

P=design internal pressure=800 KPa,

D_1=outer diameter of inner cylindrical vessel=154mm,

S_a =allowable stress=120.6MPa (for SS304L),

e=weld efficiency=0.85.

So that thickness of vessel is,

$$t_1 = \frac{800 \times 10^3 \times 154}{2 \times 120 \times 10^6 \times 0.85 + 0.8 \times 200 \times 10^3}$$

$$t_1 = 0.6\text{mm}$$

The tolerance for metric plate is 0.3mm under the standard thickness. The nominal thickness would be (0.6+0.3) =0.9mm. Therefore, we would select a nominal thickness of 3mm. The head of vessel would be simple plate type and the thickness of head would be 3mm.

According to the ASME code, Section VIII, the minimum thickness of the outer cylindrical vessel is determined as below. The critical pressure for 1.01×10^5Pa external pressures is,

$$P_c = 4\text{Pa}$$

$$P_c = 4 \times 1.01 \times 10^5$$

$$P_c = 4.05 \times 10^5\text{Pa}$$

The shell thickness may be determined from equation if the shell may be termed as a short cylinder.

$$\frac{t_2}{D_{o2}} = \left[\frac{P_c \times (1 - v^2)^{3/4} \left(\frac{L_2}{D_{o2}}\right)}{2.42E}\right]^{2/5}$$

Where,
t_2=thickness of outer cylinder,
D_{o2}=Out side diameter of outer cylinder,
v=Poisson's ratio for cylinder material=0.28,
L_2=length of cylinder=0.320m,
E=Young's modulus of cylinder material=207×10^9Pa
So that thickness will be,

$$\frac{t_2}{0.210} = \left[\frac{4.05 \times 10^5 \times (1 - 0.28^2)^{3/4} \left(\frac{0.320}{0.210}\right)}{2.42 \times 207 \times 10^9}\right]^{2/5}$$

$$t_2 = 0.9\text{mm}$$

The appropriate minimum thickness of 3mm selected. The figure from the calculated dimensions is shown as below,

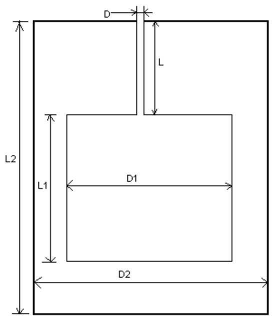

Fig.2 Schematic of cryosorption pump

VI: HEAT LOAD CALCULATION

Cryopumping means the generation of vacuum by low temperatures. Thus, the generation and availability of low temperatures is a prerequisite for the operation of cryopumps. The cryopump housing will usually be at ambient temperature, whereas the cryopanel must be refrigerated. So, there will always be heat flux onto the panel due to the different temperatures. It is essential for establishing stably low temperatures to reduce heat influx on the cold surface. The total thermal load *Q* transmitted to the cryosurface consists of the sum of heat flow rates produced by thermal conductivity of the solids, gas heat conduction, and thermal radiation. For working cryopumps the thermal loads due to cryosorption and/or cryocondensation still have to be added. These results from the enthalpy change between particle temperature and phase transition temperature ΔH_{cool}, and the phase change enthalpy ΔH_{Ph} itself. So the total heat load to the panels are given by, [4]

$$Q = Q_s + Q_g + Q_r + \Delta H_{cool} + \Delta H_p$$

Where,
Q= Total heat load,
Qs=Solid heat conduction,
Q_g=Gaseous heat conduction,
Q_r=Radiative heat transfer,
ΔH_{cool}=Enthalpy change between the molecule temperature and phase transition temperature,
ΔH_p=Phase change enthalpy

1) Solid Heat conduction:-The heat transmitted by solid conduction (e.g., via piping and instrumentation, fastenings, supply lines, cables) is proportional to the cross-section *A* and the thermal conductivity λ at the applied temperature difference (between warm wall and cold surface), and inversely proportional to the conductor's length *L*. Solid heat conduction is given by equation as under,

$$Q_s = \frac{k}{L} A$$

Where,

$$k_t = \int_{80}^{300} k(T)\ dT$$

=2711 W/m
In present apparatus the length of conductor is 105mm and outside diameter of conductor is 22mm. The conductor is hollow with thickness of 3mm. So the cross sectional area of conductor is given by,

$$A = \frac{\pi}{4}(22^2 - 16^2)$$
$$= 179.07\text{mm}^2$$
$$= 179.07 \times 10^{-6}\ \text{m}^2$$

So that Heat load due to thermal conduction is given by,

$$Q_s = \frac{2711}{105 \times 10^{-3}} \times 179.07 \times 10^{-6},$$
$$Q_s = 4.6211\text{W}$$

So the load due to solid conduction is 4.6211W.

2) Gaseous heat conduction:-The influence of residual heat conduction in the gas is due to the energy transfer within collisions between the molecules and any surface. This effect is associated with the mean free path, which denotes the average distance which a molecule travels between two successive collisions. It can be practically eliminated, when the mean free path λ between two particle hits is considerably larger than the characteristic vessel dimension *d*, which begins to hold at lower pressures. In this case, the collisions between molecules become less frequent and the molecules collide predominantly with the vessel walls. Then, the heat transfer depends only on the number of molecules and a linear relationship develops between gas heat conductivity and pressure. At higher pressures, the gaseous heat transfer is much higher and owing to convective bulk motion of the gas and the thermal conductivity of the gas does not change significantly with pressure. For free molecular conduction the mean free path is given by[4]

$$\lambda = \left(\frac{\mu}{P}\right)\left(\frac{\pi RT}{2gc}\right)^{1/2}$$

Where,
μ=gas viscosity at temperature T=300K,
=18.47×10^{-6} Pa s
P=10^{-1}Pa.

$$\lambda = \left(\frac{18.47\times10^{-6}}{10^{-1}}\right)\left(\frac{3.14\times287\times300}{2\times1}\right)^{1/2}$$

$=0.06792 > d_2-d_1=0.040$

So that free molecular conduction occurs.

The heat load due to gaseous conduction for free molecular condition may now be determined by given equation,

$$Qg = GPA_1(T_2 - T_1)$$

Now, Area of inside cylinder will be calculated from following equation,

$$A_1 = 2\times\frac{\pi}{4}D_1^2 + \pi D_1L_1 + \pi DL - \frac{\pi}{4}D^2$$

$$= 2\times\frac{\pi}{4}\times0.160^2 + \pi\times0.160\times0.180 + \pi \times 0.022\times0.105 - \frac{\pi}{4}0.022^2$$

$=0.137497\,m^2$

And Area of outside cylinder will be calculated from following equation,

$$A_2 = 2\times\frac{\pi}{4}D_2^2 + \pi D_2L_2$$

$$= 2\times\frac{\pi}{4}\times0.200^2 + \pi\times0.200 \times 320$$

$=0.263760\,m^2$

The Accommodation coefficient factor will be calculated from the given equation and a1 and a2 are accommodation coefficient for inside and outside vessel,

$$\frac{1}{F_a} = \frac{1}{a_1} + \frac{A_1}{A_2}\left(\frac{1}{a_2} - 1\right)$$

$$= \frac{1}{1} + \frac{0.137497}{0.263760}\left(\frac{1}{0.85} - 1\right)$$

$= 1.0920$

Here Accommodation coefficient factor, $F_a = 0.9158$

Now, G will be calculated from the given equation,

$$G = \frac{\gamma+1}{\gamma-1}\left(\frac{g_c R}{8\pi T}\right)^{1/2} F_a$$

$$= \frac{1.4+1}{1.4-1}\left(\frac{1\times 287}{8\times3.14\times300}\right)^{1/2} \times 0.9158$$

$= 1.0723$

Now gaseous conduction is,

$$Q_g = GPA_1(T_2 - T_1)$$

$$= 1.0723\times10^{-1}\times0.137497 \times (300 - 80$$

$= 3.2436$ □

3) Radiative heat transfer:-Under molecular flow conditions, radiant heat from the process side in the vacuum chamber and the pump body is the primary heat load on the panels. For a pump to be heated by radiation, there are two requirements. Firstly, the heat has to be emitted from the chamber, and, secondly, the pump must absorb the incident radiation. Both possibilities have to be minimized by an appropriate design.[5][6]

The radiation heat exchange between two surfaces *A*1 and *A*2 is given by,

$$Q_r = F_e\, F_{12}\, \sigma\, A_1\, (T_2^4 - T_1^4)$$

Now, Emissivity factor is given by,

$$\frac{1}{F_e} = \frac{1}{\varepsilon_1} + \frac{A_1}{A_2}\left(\frac{1}{\varepsilon_2} - 1\right)$$

For case-1-without charcoal coated cryopanel

$$= \frac{1}{0.05} + \frac{0.137497}{0.263760}\left(\frac{1}{0.1} - 1\right)$$

$= 24.6917$

And, $F_e = 0.0405$

Now, Heat load due to radiation will be given by

$$Q_r = 0.0405\times1\times\ 5.67\times10^{-8}\times0.137497\times\ (300^4 - 80^4)$$

$Qr = 2.5446$ W

For case-2-charcoal coated cryopanel. Here the panel is coated with charcoal so that it becomes the perfectly black body so that emissivity □*1* in this case will be 1,

$$\frac{1}{F_e} = \frac{1}{1} + \frac{0.137497}{0.263760}\left(\frac{1}{0.1} - 1\right)$$

$= 5.6917$

$F_e = 0.1757$

Now, Heat load due to radiation will be given by

$$Q_r = 0.1757\times1\times\ 5.67\times10^{-8}\times0.137497\times\ (300^4 - 80^4)$$

$Q_r = 11.0387$ W

4) Enthalpy transfer:-During pumping, the cryopanel must absorb the energy of the incoming particles, i.e., the enthalpy difference for cool-down between baffle temperature and panel temperature and the energy connected with the phase change in the subsequent immobilization step.[7]

In present case, enthalpy change and enthalpy of phase change are quite small and they are negligible. Hence,

$$\Delta H_{cool} + \Delta H_{ph} = 0$$

So the total heat load is given by equation is,

For case-1-without charcoal coated cryopanel

$Q = 4.6211 + 3.2436 + 2.5446 + 0$

$Q = 10.4093$ W

For case-2-charcoal coated cryopanel.

$Q = 4.6211 + 3.2436 + 11.0387 + 0$

$Q = 18.9034$ W

5) Surface temperature of cryopanel:-The surface temperature of cryopanel is calculated as below.[8]

Heat flux is given by,

$$q = \frac{Q}{A_1}$$

For case-1-without charcoal coated cryopanel

$$q = \frac{10.4093}{0.137497}$$

$q = 75.63\ W/m^2$

For case-2-charcoal coated cryopanel.

$$q = \frac{18.9034}{0.137497}$$
$$q = 137.4823\ \mathrm{W/m^2}$$

But heat flux also given by,

$$q = \frac{K(T_{outside} - T_{inside})}{dX}$$

For case-1-without charcoal coated cryopanel

$$75.63 = \frac{9.22 \times (T_{outside} - 77.3)}{0.003}$$

$$T_{outside} = 77.3246$$
$$T_{outside} = 77.4$$

For case-2-charcoal coated cryopanel

$$137.4823 = \frac{9.22 \times (T_{outside} - 77.3)}{0.003}$$

$$T_{outside} = 77.3447$$
$$T_{outside} = 77.4$$

VII: MASS FOW RATE OF LIQUID NITROGEN.

In order to achieving the vacuum, the gases left inside the vacuum chamber after roughing operation should be freezed on cryopanel. For freezing the gas molecules on cryopanel, cryopanel is cooled below the condensation temperature of gas being condensed. For the present experiment we have selected liquid nitrogen as cryogen. For effective condensation and sorption, it is desired to maintain the cryopanel temperature at 80K throughout the experiment. So it is necessary to supply LN2 continuously and mass flow rate of LN2 will be decided. [9][10]

At the normal boiling point, liquid nitrogen has a heat of vaporization of 199.3KJ/kg. The mass flow rate will be calculated from the equation,

$$Q = m \times l$$

For case-1-without charcoal coated cryopanel

$$10.4093 = m \times 199.3$$
$$m = 5.2223 \times 10^{-5}\ \mathrm{kg/s}$$

For case-2-charcoal coated cryopanel.

$$18.9034 = m \times 199.3$$
$$m = 9.4849 \times 10^{-5}\ \mathrm{kg/s}$$

IX: CONCLUSION

We have described here design of simple apparatus of cryosorption pump of pumping speed 1000 l/s and ultimate pressure of 10^{-6} Pa. The theoretical results will be compared with the actual value. As a pump has no moving parts so it can be used as vibration free vacuum pump. The apparatus is simple to use and easily accessible. The necessary detail have been given here and or further detail the authors can be contacted.

REFERENCES

[1] Basics and applications of cryopumps,*C. Day* at Forschungszentrum Karlsruhe, Institute of Technical Physics, 76344 Eggenstein-Leopoldshafen, Germany[2005].

[2] Performance evaluation of conceptual designed of single panel cryopump by Mr. Sumit Suhagiya and Prof. R.M. Srivastava [July 2012].

[3] Cryosorption-A method of simulating the space vacuum environment by NASA, Godarad space flight centre,greenbelt,Maryland,Jan26,[1965]

[4] Monte Carlo calculation of the thermal radiation heat load of the ITER pre-production cryopump Xueli Luo, Volker Hauer, Christian Day[2012].

[5] MOLECULAR SURFACE PUMPING: CRYOPUMPING**,** *C. Benvenuti* at CERN, Geneva, Switzerland.[2000]

[6] Experimental assessment of the ITER cryosorption pump high temperature regeneration Chr. Day, H. Haas, Fusion Engineering and Design 84 [2009 665–668

[7] Design rules for vacuum chambers, C. Hauviller, CERN, Geneva, Switzerland[2007]

[8] Cryogenics systems by Randall F.Barron, Published by Oxford University press, New York.

[9] Cryogenic heat transfer by Randall F.Barron, Published by Taylor and Francis, Philadelphia

[10] Modern Vacuum practice by Nigel S. Harris, McGraw-hill book company.