Experimental Verification of Capture Coefficients for a Cylindrical Cryopanel of Closed Cycle Refrigerator Cryopump

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Abstract. A closed cycle refrigerator based cryopump of 1000 lit/s pumping speed for nitrogen was developed, using indigenously developed two stage GM-cryocooler at cryogenic section of Raja Ramanna Centre for Advanced Technology (RRCAT). Performance tests of cryopump were carried out to establish cool-down time, ultimate pressure, pumping speed, crossover rating, maximum throughput and gas capacity for nitrogen. This cryopump has successfully completed more than 4,000 hrs of operation. Capture coefficient or pumping efficiency for cylindrical cryopanel of this cryopump was calculated by method reported by J W Lee and Y K Lee. This method uses geometric view factors between surface elements of cryopump. The effect of cryopanel diameter on the pumping characteristics of the nitrogen (Type-II gas) was studied for this cryopump and experimentally verified by carrying out pumping speed tests of nitrogen with different cryopanel diameter in our laboratory. The calculated values of capture coefficients for this cryopump gave reasonably good agreement with the experimental values.

1. Introduction

Refrigerator cooled cryopump provides ultra clean vacuum and has very high pumping speed for water vapour as well as for other gases, high cross over capability and other benefits [1]. This makes refrigerator cooled cryopump a pump of choice for applications demanding a clean, oil-free vacuum with fast pump down cycle to high vacuum in most varied areas of vacuum technology.

The efficiency of cryopump or total capture coefficient of cryopump, c is given by the ratio of the actual pumping speed of cryopump to the theoretical maximum (black hole) pumping speed $S_{\text{bd}}$. Therefore actual pumping speed, S is given by [2]:

$$ S = c \cdot S_{\text{bd}} = c \cdot A \cdot \left( \frac{RT}{2\pi M} \right)^{1/2} $$  \hspace{1cm} (1.1)

Where, A is a projected inlet area of pump, T is temperature and M is molecular weight of gas being pumped. The total capture coefficient is a function of the internal pump geometry and the sticking coefficient of gas on cryopanel. Hence, one has to calculate capture coefficient for a given

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cryopanel geometry of cryopump. The total capture coefficient can be easily estimated for geometries, where inlet cross-section, baffle and cryopanel are parallel, as in this type of refrigerator cryopumps. Total capture coefficient, c can be expressed by Oately’s law [2]

\[
\frac{1}{c} = \frac{1}{Pr} + \frac{1}{W_b} - 1
\]  

(1.2)

Where, \(W_b\) is the transmission probability of baffle/louvers, mounted on inlet side of radiation shield and Pr is the capture probability of the gas particle at the cryosurface/cryopanel. This capture probability; Pr is a function of cryopanel geometry and sticking coefficients of particle on surface.

In cryogenic section of RRCAT, a prototype closed cycle refrigerator cooled cryopump has been developed using indigenous two-stage GM cryocooler. This cryopump has inlet diameter of 200 mm (8 in.) and designed for pumping speed of 1000 l/s for nitrogen [1]. Figure 1 shows the schematic of cryopump. The capture probability or coefficient; Pr for cylindrical cryopanel of this cryopump was calculated with view factor method reported by J W Lee and Y K Lee [3]. This method is easy, accurate and fast for investigating the effect of cryopanel geometry on the pumping characteristics of cryopanel surfaces for different gases.

Figure 1. Schematic diagram of cryopump

This article investigates the effect of geometrical parameters, such as diameter, height of cylindrical cryopanel for concerned cryopump on the pumping characteristics of gases. Calculated values of capture coefficient for type II gas were validated by carrying out pumping speed measurement tests of nitrogen with cryopanels of different diameter. The calculated values of capture coefficients for this cryopump gave reasonably good agreement with the experimental values.

2. Calculation of capture probability of cryopump

In cryopump various types of gas are pumped on surfaces of panel by different mechanism as shown in figure 1. Gases like H\(_2\)O, CO are type-I gases and condensed on the baffle maintained at the temperature of 80 -100 K. Gases like N\(_2\), O\(_2\), Ar are called type-II gases. These gases are pumped by cryocondensation on the surface of cryopanel whereas type-III gases like H\(_2\), H\(_2\) are cryosorbed by sorption stage of activated charcoal on reverse side of the panel. If the major gas load is of type II gases of N\(_2\), O\(_2\), Ar then diameter of cryopanel should be as large as possible so that most of the gas molecules entering the pump through a louver can be intercepted by and condensed on the front
surface of the panel. However, when the gas load of H\textsubscript{2} and He is appreciable, there should be an optimum size for the cryopanel. Hence, from the design point of view, optimum value exists for size, shape and position of the cylindrical cryopanel within radiation shield of cryopump [3].

J W Lee and Y K Lee suggested an efficient view factor method for calculation of capture coefficient or probability of cylindrical cryo array of cryopump [3]. They have reported the theoretical basis, formulation, accuracy and speed of this method in detail.

2.1 Brief review of formulation of method: This formulation is analogous to that of thermal radiation exchange between diffuse surfaces of an enclosure [3]. The molecular flux balance on k\textsuperscript{th} surface will give following equations.

\[ n_k = n_{o,k} - n_{i,k} = n_{o,k} - \sum_{j=1}^{N} F_{kj} n_{o,j} \Rightarrow n_k = \sum_{j=1}^{N} (\delta_{kj} - F_{kj}) n_{o,j} \]  \( (2.1) \)

\[ \sum_{j=1}^{N} \delta_{kj} - (1 - f_k) F_{kj} \int n_{o,j} = n_{e,k} \]  \( (2.2) \)

In this method, one has to solve N matrix equations (2.2) for N surface elements of cryopump (or any vacuum component considered) to have outgoing molecular fluxes; \( n_{o,j} \) in terms of molecular flux due to self emission or introduction of source; \( n_{e,k} \), sticking coefficient \( f_k \) and view factors; \( F_{kj} \). Therefore, net molecular flux; \( n_k \) can be found from equations (2.1) and \( n_{o,j} \). So the differential pumping action on each pumping surface can be obtained if only the view factors, sticking coefficients, and gas source flux distribution (may be due to evaporation or source-gas introduction) are known. If there are k entrance surface elements and m pumping (or exit) surface elements of pump then the capture coefficient or probability, \( P_r \) of a cryo array can be written as,

\[ P_r = \frac{\sum_{i=1}^{m} n_{i,j} \cdot A_i}{\sum_{j=1}^{k} n_{e,k} \cdot A_j} \]  \( (2.3) \)

3. Study of pumping characteristics for concerned cryopanel configuration:

The view factor method was applied for calculating capture coefficient of cylindrical cryopanel of cryopump developed at RRCAT. Theoretical study for the effect of geometrical parameters of cryopanel on pumping characteristics of gases has been done.

3.1 Description of cryopump configuration for analysis: The present cryopump has ‘O’ ring sealed high vacuum flange of 200 mm (8 in.) inlet diameter and built around indigenous two-stage GM cryocooler. The configuration is shown schematically in figure 2. The surface 1 is louver of 60° angle mounted on thermal radiation shield of Ø180 mm (surface 2 in figure 2) with aspect ratio of Do/Ho ~ 1.0. This is the first stage array of cryopump, mounted on first stage cold head of 80K. Second stage cryopanel has shape of cylindrical inverted cup (surface 3) and has sorption stage of activated charcoal on reverse side. This is mounted on second stage (20K) cold head of GM cryocooler. These cryopanels were made of pure copper sheet. Since we considered here calculation of capture coefficients of type II and type III gases on cryopanel and the effect of geometrical parameters of cryopanel on pumping characteristics, sticking coefficient on radiation shield can be assumed as zero. The molecular fluxes of type II and type III gas, entering the cryopump through louver (surface 1) assumed to be uniformly distributed over surface 1 and distribution is directionally diffused following cosine law. The sticking coefficient of gas molecules on the front surface of cryopanel; \( f_o \) and on the back side is \( f_i \). Then the capture probability of this configuration is defined as the ratio of gas molecules captured on surface 3 to the gas molecules introduced from surface 1. Pumping efficiency or total capture
The coefficient of cryopump body can be obtained by equation (1.2) of Oately's law between the transmission probabilities of the baffle and the cryopanel [3, 6]. The pump surface (cryopanel, radiation shield and baffle surface) is divided into 20 surface elements instead of 50 surface elements considered by Lee. The reason for preferring fewer elements is not only to reduce computing time of view factor calculation but to compare the results obtained using 20 surface elements with results obtained by Lee for 50 surface elements and also with experimental values for type II gas. The view factor between surface elements is calculated by the Monte Carlo method with 3000-5000 particles emitted from each surface element into random directions in order to satisfy the diffuse condition described above.

3.2 Discussion on effect of concerned cryopanel geometry on pumping characteristics: The influence of three geometrical parameters is considered here for a cylindrical cryopanel namely; diameter $D_o$, length or vertical height of panel $H_i$ and $H_c$ is the gap between panel front surface and baffle. Variation of capture probability or coefficient, $P_r$ with these parameters is shown in figures 3 to 6, for both type II and type III gases. For type II gases, both sticking coefficient on front surface, $f_o$ and on reverse side $f_i$ are taken as 1.0, but for type III gases $f_i \sim 1.0$ and $f_o = 0.0$. The diameter of radiation shield $D_o$ and height $H_o$ are fixed with diameter $D_o = 18$ cm. and $D_o/H_o \sim 1.0$.

For type II gases, capture probability increases monotonically with $D_i$ where $D_i/D_o$ is increasing from 0.5 to 0.9 (figure 3). Increasing the gap, $H_c$ results in a reduced capture probability because a larger gap increases chances of molecules striking with a shield wall and returning to the baffle. The height of cryopanel has negligible effect on the capture coefficient and even less for the large diameter as shown in figure 4. For type III gases, the capture probability does not increase linearly with $D_i$ but...
cryopanel has an optimum diameter, at which the capture probability has maximum value. For the diameter much larger or much smaller than this optimum value, capture probability or efficiency decreases [3]. Variation of capture probability for type III gases with $D_i$ is shown in figure 5 where result obtained for 20 surface elements is compared with that obtained by Lee for 50 surface elements. It can be observed that there is shift in capture probability values but optimum diameter ratio of $D_i/D_o$ is $\sim 0.6$ in both cases (figure 5) regardless of the number of surface elements considered in analysis. Increased $H_i$ results in a reduced capture probability for type III gases as gas molecules have to travel longer distance to get capture on reverse side of panel. The effect of $H_i$ is shown in figure 6. A cylindrical cryopanel of optimum diameter has the highest capture efficiency, irrespective of height or skirt length of cryopanel.

4. Experimental verification:
In order to validate the calculation of capture coefficients for type-II gases, laboratory tests were performed for pumping speed measurement of cryopump using nitrogen (type-II gas). Five numbers of

Figure 5. Variation of capture probability, $Pr$ with $D_i$ of cylindrical cryopanel for type-III gases

Figure 6. Variation of capture probability, $Pr$ with $H_i$ of cylindrical cryopanel for type-III gases

Figure 7. Schematic of test set-up

Figure 8. Photograph of test set-up
second stage copper cryopanels of different diameter, ranging from 0.5-0.9 times the diameter of radiation shield were fabricated and used in these tests to verify experimentally the effect of cryopanel diameter on capture coefficients for nitrogen (type-II gas). The radiation shield of Ø 180 mm was used with same concentric louver in all these tests as a first stage array of cryopump.

4.1 Experimental set-up for pumping speed measurement: The tests for pumping speed measurement of nitrogen were carried out by constant pressure flow meter method. Recommended practices were followed in preparing; operating the vacuum test equipments and test procedure [1, 4 and 5]. AVS single test dome constructed of electro-polished stainless steel was used in unbaked condition. Test dome was mounted directly on cryopump as shown by schematic of test set-up in figure 7. This same test set-up was also used for measurement of crossover rating and gas capacity for nitrogen of cryopump [1]. The mass flow rate or throughput of nitrogen in-leaked into test dome was measured by thermal mass flow meters of M/s. MKS Instruments. Pressure in test dome was measured with stabil-ion gauge of M/s. Granville-Phillips which is a BA gauge with claimed accuracy of ± 4 to 6 %. Calibrated Si-diode of M/s. LakeShore Cryotronics was used to monitor the cryopanel temperature. For nitrogen gas, a small liquid nitrogen cryocontainer was used. The photograph of test set-up is shown in figure 8.

4.2 Comparison with calculated capture coefficient and discussions: The measured pumping speed values of nitrogen for all five cryopanels give experimental values of total capture coefficient, $C_{\text{exp}}$. Since same louver assembly was used in all tests, transmission probability of louver remained constant. So experimental values of capture probability or coefficient of cryopanel; $Pr_{\text{exp}}$, can be readily obtained from equation (1.2). Calculated values of capture probability; $Pr$ are compared with experimentally obtained capture probabilities for all five panels with different $D_i$ in table 1. Calculated capture probabilities; $Pr_{20}$ using 20 surface elements of cryopump are also compared with those using 50 surface elements; $Pr_{50}$ given by Lee [3]. Capture probability values reported by Lee, for 50 surface elements were published in graphical form and numerical values were inferred from these graphs. There is difference of ~ 3 to 4 % between capture probabilities calculated with 20 surface elements and those with 50 surface elements. Calculated capture probabilities; $Pr$ differ by ~ 6-10% of experimental values regardless of the number of surface elements considered in computation. Total capture coefficient values differ by ~ 4 - 5 % of experimental values. So calculated capture coefficients with few surface elements gave reasonably good agreement with experimental values of capture coefficients for type-II gas. But the use of sufficiently large number of surface elements is beneficial for analyzing the effect of parameters such as sticking coefficient on type III gases and for precise calculation of regional pumping rates of surfaces. Variation of theoretically calculated capture coefficients with diameter of panel is shown graphically along with experimental values in figure (9)

**Table 1.** Comparison of calculated capture coefficients with experimental values.

| Do/Di | Calculated capture probability; $Pr_{20}$ for N = 20 | Calculated capture probability; $Pr_{50}$ for N = 50 | Experimental value of capture probability $Pr_{\text{exp}}$ | Calculated capture coefficient; $C_{20}$ for N = 20 | Experimental total capture coefficient; $C_{\text{exp}}$ |
|-------|--------------------------------------------------|--------------------------------------------------|--------------------------------------------------|--------------------------------------------------|--------------------------------------------------|
| 0.5   | 0.644                                           | 0.670                                           | 0.600                                           | 0.359                                           | 0.342                                           |
| 0.6   | 0.680                                           | 0.720                                           | 0.622                                           | 0.375                                           | 0.354                                           |
| 0.7   | 0.744                                           | 0.780                                           | 0.668                                           | 0.390                                           | 0.368                                           |
| 0.8   | 0.787                                           | 0.825                                           | 0.710                                           | 0.401                                           | 0.380                                           |
| 0.9   | 0.840                                           | 0.870                                           | 0.775                                           | 0.419                                           | 0.398                                           |

*a Calculated capture probabilities given by J. W. Lee and Y. K. Lee.*
5. Summary:

Total capture coefficient or efficiency of a cryopump depends in a complex way on internal geometry and on sticking coefficient of gases on cryopanel. An efficient view factor method, reported by J. W. Lee and Y. K. Lee is easy and fast for investigating the effect of cryopanel geometry on the pumping characteristics for different gases. Capture coefficient was calculated for present cryopump configuration and the effect of geometrical parameters of cryopanel on pumping characteristics of gases was studied. Calculated capture probability values for type-II gas were validated by carrying out pumping speed measurement tests of nitrogen on cryopanels of different diameter. Calculated capture coefficient gave reasonably good agreement with experimental values for nitrogen (type-II) gas taking few numbers of surface elements for computation. Similarly, experimental verification of capture coefficients for type-III gases like hydrogen can be done.

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