Design of Prototype Internal 20k Helium Gas Purification System for Helium Plant & Test Facility

Dhaval B. Prajapati  
M.E. Student  
Department of Mechanical Engineering  
L.D. College of Engineering, Ahmedabad

A. K. Sahu  
Scientist-Engineer SF  
Department of Devision Head, LCPC  
Institute for Plasma Research, Bhat, Gandhinagar.

J. M. Patel  
Associate Professor  
Department of Mechanical Engineering  
L.D. College of Engineering, Ahmedabad

Abstract

The Helium Refrigerator/Liquefier (HRL) plant being designed at IPR will have in-built helium purification system for removal impurities of hydrogen and trace of neon at 20K by using charcoal. To remove such impurities, adsorber bed is required to use at 20K, which, otherwise, can choke up of the pipe lines and valves leading to large pressure drop and inefficient liquefaction process, it may get condensed and frozen, which can destroy the blades of turbines of HRL. For the actual size purifier, the amount of inlet H2 impurity in the helium stream is about 100 PPM (parts per million) by volume and that at the outlet of the bed it should have less than 5 PPM. The design of this prototype purification bed will be done based on the design and analysis of the actual purification bed and associated filter elements done during 2013-2014. This prototype will include necessary heat exchangers required to reach a temperature in between 20K to 25K, along with the bed. Cold helium will be used to reach such low temperature. The adsorber bed design includes calculation & optimization of size of adsorber bed, the pressure drop and MTZ length calculation using Rosen Model and Axial Dispersion Model and Heat Exchanger design include calculation and optimization of its length, tubes’ diameter & Pressure drop across it. Veracity of this test facility design will be tested during experiment.  

Keywords: Hydrogen Adsorption At 20K, Adsorber Bed, Helium Purification System, Tube-In-Tube Heat Exchanger, Filter

I. INTRODUCTION

Prototype of adsorber bed is a model of an actual adsorber bed which will be used to test the adsorption capacity of different adsorbents & capability of the adsorber bed of removing impurities of H2 & trace of neon from the supplied Helium gas at 20K. Direct use of the adsorber bed in the Indigenous Helium Plant might cause the problem of the inaccuracy and ineffectiveness in purifying helium gas & if it may not be capable to purify helium gas at required level of purification of less than 5PPM output than that might be more expensive to correct that design and implement new corrected bed during the operation. So, before applying that adsorber bed in the Indigenous Helium plant, it is essential to test on the prototype adsorber bed. This prototype will work on the same principle and temperature (20K) as of the actual one.

To test the adsorber bed, the test facility should necessitate developing. This adsorber bed test facility’s proposed design contains one adsorber bed, one filter element and two heat exchangers: one tube in tube type and another is LHe bath type heat exchanger. Then it optimized to one adsorber bed, one filter element and one heat exchanger: three stream tube in tube type heat exchanger. This adsorber bed test facility will operate at 20K and with the less mass flow rate of helium gas than that of the HRL plant [1].
And considering 14 bar & 20K operating pressure & temperature, 100PPM impurity inlet & 1 PPM outlet, 1g/s mass flow rate of helium gas with impurity and time of operation is 1 day. The process flow schematic of adsorber test facility is shown in Fig. 1.

II. ADSORBER BED

Adsorber bed is the purifier which is used to purify the helium gas from the impurity of Hydrogen and trace of Neon gas. But there are in comparison neon impurity is negligible & most of the part of the impurity is of H2 which may come from the compressor system. The adsorber bed works on the isothermal process at 20K. To maintain isothermal process the whole adsorber bed will be covered with vacuum jacketed insulation.

A. Adsorbent Selection:

Activated carbon is the most widely used sorbent. Its usefulness derives mainly from its large micropore and mesopore volumes and the resulting high surface area. For having a good rate of adsorption it is very important to know about the physical property of adsorbents [2].

Now a days, there are many adsorbents used for different application in the adsorber bed. Here, we need to get adsorbed the main impurities of H2 and trace of Neon for the purification of the helium at 20K & it is finally observed that the Adsorption capacity of Activated charcoal is higher than the any other adsorbent at low temperature and higher pressure [1].

There are different kind of activated charcoal available in the market out of them, here, it was taken ACF (Activated Charcoal Fibre Clothe type), SC 11 (Coconut shell based activated charcoal) & KL3 (Carbon Black) for numerical calculation and comparison, as shown in fig. 2.

Fig. 2(a) shows the comparison of different activated charcoals for their hydrogen adsorption capacity with respect to relative pressure at 20K. As the relative pressure increases the hydrogen adsorption capacity of the charcoals increasing. Out of all these three activated charcoal, SC 11 – Coconut shell based charcoal shows the better adsorption capacity than any other for the same.
Fig. 2: (a) Hydrogen Adsorption Capacity of Different Activated Charcoal at 20K

Fig. 2: (b) Hydrogen Volume Adsorption on Different Activated Charcoal

Fig. 2: (c) Amount of Adsorbents required to adsorb Hydrogen Impurity

Fig. 2: Comparison of Different Activated Charcoals

Fig. 2(b) shows the comparison of activated charcoals for H2 volume to be adsorbed with respect to relative pressure. Here also, Coconut shell based charcoal adsorb much more volume than KL3 & ACF. Fig. 2(c) shows the mass of adsorbent required for different Impurity level. From the graph, mass requirement of coconut shell based charcoal is less than other activated charcoal. So, from the graphs, it is concluded that Coconut Shell based Activated Charcoal is better than any other activated charcoal for hydrogen adsorption at 20K & is selected because it provides better adsorption capacity than any other adsorbent & also provide micropore structure in granular size which will provide effective trapping of small gas molecules with higher surface area 200-1200 m2/g [3].
B. Mass of Adsorbent & Saturation Length:

To calculate the mass of adsorbent required for the hydrogen adsorption, DR calculation Model theory is selected for the calculation of the pore size [1, 4]. This Mass of hydrogen adsorbed describe the adsorption capacity of the coconut shell type activated charcoal, for different ppm level the adsorption capacity changes which is shown below.

![Graph of Impurity Vs Hydrogen Adsorption Capacity At 20K of Coconut Shell Based Activated Charcoal](image)

Fig. 3: Impurity Vs Hydrogen Adsorption Capacity At 20K of Coconut Shell Based Activated Charcoal

This graph of fig.3 describes that as the ppm level increases, in the beginning, the adsorption capacity increases rapidly but after some levels it increasing very slowly.

![Graph of Hydrogen Isotherm at 20K for Coconut Shell Based Activated Charcoal](image)

Fig. 4: \( \text{H}_2 \) Isotherm at 20K for Coconut Shell Based Activated Charcoal

Fig.4 describes the graph which says, as the relative pressure of impurity increases, in the beginning, the adsorption capacity increases rapidly but after some level it increasing very slowly. This graph is called as Hydrogen Isotherm (at 20K). Fig.5 describes the adsorption capacity of charcoal with respect to volume get adsorbed of hydrogen impurity from the helium gas. This graph says, as the amount of volume gets adsorbed on the charcoal increasing, its adsorption potential is decreasing. Fig.6 shows the mass of adsorbent required for different impurity level. Here, for 100PPM impurity, 1 g/s mass flow rate and 1 day operation time, mass of coconut shell based activated charcoal required is 0.142Kg– 0.150Kg.

![Graph of Characteristic Curve of Hydrogen at 20K on Coconut Shell Based Activated Charcoal](image)

Fig. 5: Characteristic Curve of Hydrogen at 20K on Coconut Shell Based Activated Charcoal
This charcoal occupied the length in the bed of 2 inch (ID = 0.0548m) [5] pipe is 0.1097m, which is called as saturation length. And for the 1m length and 2 inch diameter of the adsorber bed, it can take approx. 22.40hrs (0.93~1days) to saturate whole bed for 100ppm impurity level & 0.0285 Kg/Kg adsorption capacity.

Fig. 6 shows the variation in Saturation Length with impurity level for different mass flow rates. As the impurity level increases, the saturation length required for the selected operation time is increases & saturation length also increases with increase in mass flow rate.

**C. MTZ Length & Adsorber Bed Length:**

There are various analytical models proposed to predict the MTZ Length, out of them two very successful models are stated below [6, 7].

1) Axial Dispersion Model & 2. Rosen Model:
Considering length of the bed, L=1m and diameter of bed, D=2inch & operation time of 1 day. From the above models and parameters, we got following results for the MTZ Length as shown in fig. 8 & 9.

**Fig. 8: Concentration Ratio versus Time Graph of Rosen Model**
From the above result of Rosen Model (Fig. 8), break through time, \( t_b = 173201 \text{s} \) & saturated time, \( t_s = 305201 \text{s} \) & from the axial dispersion model (Fig. 9), break through time, \( t_b = 243201 \text{s} \) & saturated time, \( t_s = 324001 \text{s} \); So, MTZ time, \( T_{MTZ} \) for Rosen and Axial Dispersion comes 36.67hrs & 22.44hrs respectively.

Fig. 10 (a) & (b) show the MTZ Time for different mass flow rates & related interstitial velocity and different charcoal particle diameters, whose variations remain almost same for the both of the models. Fig 10 (I) of (a) & (b) indicate that as the mass flow rate (or interstitial velocity) increase the MTZ Time decrease. Fig 10 (II) of (a) & (b) indicate that as the charcoal particle size increase the MTZ Time increase. In fig. 10 MTZs term is indicated for the MTZ Time.

The graphs of the fig. 10 are plotted for the MTZ Time for different impurity level & for any impurity level it remains unchanged. It means, here, in one graph, one plotted line shows the data for any impurity level.
With increase in impurity level, breakthrough time, \( t_b \) and saturation time, \( t_s \) should be decrease, but according to the result the value of \( t_b \) & \( t_s \) remains constant which is unaccepted because as the impurity level increases (for the same mass flow rate, for the same bed & for the same operation time) the time required for the breakthrough & saturation of the bed should be decrease logically. But here it remains constant for different impurity level which is not acceptable. Reason for this problem is, the models used here for calculating MTZ length, breakthrough time and saturation time, are not related to adsorption capacity of adsorbent at all. Due to which Rosen and Axial dispersions data remain constant for different impurity level. So, it is advisable to use only difference of breakthrough time and saturation time, called MTZ time, from the Rosen and Axial Dispersion Models for further calculation of MTZ Length as described below:

1) Method: 1: This method is using the same time difference of breakthrough time and saturation time as the MTZ time.

Now, MTZ length can be calculated by,

\[
\frac{L_{Total}}{T_{Tsat}} = \frac{L_{MTZ}}{T_{MTZ}} \quad (1)
\]

Where, \( L_{Total} \) = Total Length of the Bed, m;
\( L_{MTZ} \) = MTZ Length of the Bed, m;
\( T_{Tsat} \) = Saturation Time to Saturate \( L_{Total} \), hrs;
\( T_{MTZ} \) = Time that Impurity Cross the \( L_{MTZ} \), hrs

For, 100 ppm impurity level, \( L_{Total} = 1 \) m and diameter of bed, \( D=0.054792 \) mm (2inch), 1g/s mass flow rate & operation time of 1 day, we are supplying the helium gas with impurity at 300K and 14 bar pressure to heat exchanger to cooled down its temperature up to 20K whose densities are as follows:

\( \rho_{He} = 2.2322 \) Kg/m\(^3\) [8] & \( \rho_{H_2} = 1.1223 \) Kg/m\(^3\) [8] at 300K & 14 bar, and density of the coconut shell based activated charcoal is 550 Kg/m\(^3\).

Volume flow rate of helium = Mass flow rate/ \( \rho_{He} \)

\[
= 1 / 2.2322 \approx 0.0004479 \text{ m}^3/\text{s}
\]

Impurity of Hydrogen is 100PPM, so, volume flow rate of Hydrogen is,

Volume flow rate of Hydrogen = 0.0004479*100/10\(^6\)

Therefore, Mass flow rate of \( H_2 \) = 4.479*10\(^{-8}\)*1.1223

\[
= 5.0276*10^{-8} \text{ Kg/s} = 5.0276*10^{-5} \text{ g/s}
\]

And, Volume of the Bed can be given by,

\[
V_{bed} = \frac{\pi}{4}D^2L_{Total}
= 3.14/4*0.054792^2*1
= 2.357E-03 \text{ m}^3
\]

If the whole bed is filled with charcoal then the mass of charcoal required is,

\[
M_{ads} = V_{bed} \times \rho_{charcoal} = 2.357E-03*550 = 1.2960 \text{ Kg}
\]

And, adsorption capacity of charcoal at 20K & 14 bar is 0.02852 Kg/Kg.

So, Time required (\( T_{Tsat} \)) to pass the \( L_{Total} = 1 \) m bed of 0.054792m diameter can be given by,

\[
= M_{ads} \times \frac{\text{Adsorption Capacity}}{m_{H_2}}
= 1.2960*0.02852/5.0276*10^{-8}
= 735358 \text{ sec}
\]

So, \( T_{Tsat} = 204.266 \text{ Hrs} \)

Now, form the above data, \( L_{MTZ} \) can be calculated as below;

For Rosen Model:

\[
\frac{L_{Total}}{T_{Tsat}} = \frac{L_{MTZ}}{T_{MTZ}}
\]

\[
\therefore 1/204.266 = L_{MTZ} / 36.67
\]

\[
\therefore L_{MTZ} = 0.1795 \text{ m}
\]

For Axial Dispersion Model:
MTZ length and the MTZ time is changing with different parameters like Impurity level, mass flow rate, adsorber bed diameter & length as shown in fig. 10 to 16. Here, it is selected three different mass flow rate 0.5 g/s, 1 g/s & 1.5 g/s; two adsorber bed pipe diameter 1 inch & 2 inch pipe; and different impurity levels from 10 PPM to 2000 PPM of Hydrogen impurity in Helium gas.

\[
\begin{align*}
\text{MTZ length} & = \frac{1}{204.266} = \frac{L_{MTZ}}{22.44} \\
\text{Therefore, for being on safer side, Rosen Model is most preferable with maximum value of MTZ Length which is 0.1795m.}
\end{align*}
\]

Fig. 11 describes the MTZ variation with Different Mass flow Rates, Bed Diameters & Impurity Levels. MTZ length increases very negligibly with increase in mass flow rate 0.5g/s to 1.5g/s; decreases with increase in adsorber bed diameter & decreases as the impurity level reduced as shown in below table: 1:

<table>
<thead>
<tr>
<th>Mass Flow Rate, mHe (g/s)</th>
<th>Pipe Dia.= 1”</th>
<th>Pipe Dia.= 2”</th>
<th>Pipe Dia.= 1”</th>
<th>Pipe Dia.= 2”</th>
<th>Pipe Dia.= 1”</th>
<th>Pipe Dia.= 2”</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 PPM</td>
<td>100 PPM</td>
<td>500 PPM</td>
<td>1000 PPM</td>
<td>10 PPM</td>
<td>100 PPM</td>
</tr>
<tr>
<td>0.5</td>
<td>0.0206</td>
<td>0.0161</td>
<td>0.2026</td>
<td>0.1586</td>
<td>1.0036</td>
<td>0.7857</td>
</tr>
<tr>
<td>1</td>
<td>0.0233</td>
<td>0.0183</td>
<td>0.2293</td>
<td>0.1795</td>
<td>1.1357</td>
<td>0.8892</td>
</tr>
<tr>
<td>1.5</td>
<td>0.0252</td>
<td>0.0197</td>
<td>0.2472</td>
<td>0.1938</td>
<td>1.2247</td>
<td>0.9600</td>
</tr>
</tbody>
</table>

But, MTZ time remains constant for different impurity level which supplied to the adsorber bed. Change in impurity level is not affecting the time required by the impurity to cross the MTZ length. But as the diameter of the adsorber bed is increases 1 inch to 2 inch the MTZ time increases from 12.05hrs to 36.67hrs.

Fig. 12: MTZ Time for Different Mass flow Rates, Bed Diameters & Impurity Levels
Fig. 12 mention that as the mass flow rate increase from 0.5 g/s to 1.5 g/s the MTZ time decreases as shown in below table. It is clear that MTZ time remain same for different impurity levels but increases with increase in bed diameter.

<table>
<thead>
<tr>
<th>Mass Flow Rate, mHe (g/s)</th>
<th>T\text{MTZ} (hrs) Bed Dia. = 1&quot;</th>
<th>T\text{MTZ} (hrs) Bed Dia. = 2&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>21.31</td>
<td>64.79</td>
</tr>
<tr>
<td>1</td>
<td>12.06</td>
<td>36.67</td>
</tr>
<tr>
<td>1.5</td>
<td>8.67</td>
<td>26.39</td>
</tr>
</tbody>
</table>

Fig. 13: (a) Time Required Saturating Unit Length of 1" Bed

Fig. 13: (b) Time Required to Saturate Unit Length of 2" Bed

Fig. 13 (a) & 13 (b) shows the saturation time required for the unit length & different diameters of the bed. The saturation time is decrease with increase in mass flow rate and impurity level & as the diameter of the bed increases the saturation time of the bed increases for the same length. Following table: 3 (A) & (B) shows the saturation time of the unit length of the bed for different diameter and mass flow rates.

<table>
<thead>
<tr>
<th>Mass Flow Rate, g/s</th>
<th>10 PPM</th>
<th>100 PPM</th>
<th>500 PPM</th>
<th>1000 PPM</th>
<th>2000 PPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1030.17</td>
<td>105.17</td>
<td>21.23</td>
<td>10.64</td>
<td>5.34</td>
</tr>
<tr>
<td>1</td>
<td>516.58</td>
<td>52.58</td>
<td>10.61</td>
<td>5.32</td>
<td>2.67</td>
</tr>
<tr>
<td>1.5</td>
<td>344.39</td>
<td>35.06</td>
<td>7.08</td>
<td>3.549</td>
<td>1.78</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mass Flow Rate, g/s</th>
<th>10 PPM</th>
<th>100 PPM</th>
<th>500 PPM</th>
<th>1000 PPM</th>
<th>2000 PPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>4013.42</td>
<td>408.53</td>
<td>82.47</td>
<td>41.37</td>
<td>20.74</td>
</tr>
<tr>
<td>1</td>
<td>2006.71</td>
<td>204.27</td>
<td>41.23</td>
<td>20.68</td>
<td>10.37</td>
</tr>
</tbody>
</table>
From the beginning of the operation as the gas supplied, the time required to saturate the whole adsorber bed is this saturation time & the bed will be saturate when the MTZ cross the whole bed. It means MTZ time should be less than the saturation time. But according to derived data of MTZ time as shown in table: 2, as we go for higher impurity level, saturation time decreases, which goes lower than that of the MTZ length, which shows error may be because the Rosen and Axial Dispersion model do not contain the relation with impurity level and adsorption capacity of the adsorbent. So, it can be concluded that the MTZ time which we got here may be it has any fault at somewhere. So, it cannot use MTZ Length directly.

2) Method: 2: In this method to calculate the MTZ length and breakthrough time it is used the linear difference of the time and calculate breakthrough time from whole bed saturation time which described as below:

For 100PPM, 1g/s, 1m length and 2” diameter of bed, the saturation time of the whole bed comes 204.27hrs ~ 735372s and for Rosen model:

Saturation time, \( t_s = 305201s \) = 84.77hrs &
Breakthrough time, \( t_b = 173201s \) = 48.11hrs.

So, new breakthrough time can be given by,

\[
(204.27*48.11)/84.77 = 115.93 \text{ hrs} \\
\sim 417350s.
\]

So, MTZ time can be given by,

\[
\text{MTZ time} = \text{Saturation time} - \text{Breakthrough time} \\
= 735372 - 417350 \\
= 318022s \sim 88.34\text{hrs}.
\]

Now, MTZ length can be calculated by using eq. (1),

\[
\frac{L_{Total}}{T_{Sat}} = \frac{L_{MTZ}}{T_{MTZ}}
\]

\[
\therefore \frac{1}{204.27} = \frac{L_{MTZ}}{88.34}
\]

\[
\therefore L_{MTZ} = 88.34/204.27 \\
\therefore L_{MTZ} = 0.4324 \text{m}
\]

![Fig. 14: MTZ Length with Different Parameters](image)

Table - 4

(a): MTZ Length (m) for Different Parameters with 1” Bed diameter

<table>
<thead>
<tr>
<th>Inlet PPM</th>
<th>1”Dia, 0.5m Length</th>
<th>1”Dia, 1m Length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5g/s</td>
<td>1g/s</td>
</tr>
<tr>
<td>10</td>
<td>0.31</td>
<td>0.33</td>
</tr>
<tr>
<td>100</td>
<td>0.31</td>
<td>0.33</td>
</tr>
<tr>
<td>500</td>
<td>0.31</td>
<td>0.33</td>
</tr>
<tr>
<td>1000</td>
<td>0.31</td>
<td>0.33</td>
</tr>
<tr>
<td>2000</td>
<td>0.31</td>
<td>0.33</td>
</tr>
</tbody>
</table>
Table - 4
(b): MTZ Length (m) for Different Parameters with 2” Bed diameter

<table>
<thead>
<tr>
<th>Inlet PPM</th>
<th>2”Dia, 0.5m Length</th>
<th>2”Dia, 1m Length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5g/s 1g/s 1.5g/s</td>
<td>0.5g/s 1g/s 1.5g/s</td>
</tr>
<tr>
<td>10</td>
<td>0.26 0.28 0.30</td>
<td>0.39 0.43 0.46</td>
</tr>
<tr>
<td>100</td>
<td>0.26 0.28 0.30</td>
<td>0.39 0.43 0.46</td>
</tr>
<tr>
<td>500</td>
<td>0.26 0.28 0.30</td>
<td>0.39 0.43 0.46</td>
</tr>
<tr>
<td>1000</td>
<td>0.26 0.28 0.30</td>
<td>0.39 0.43 0.46</td>
</tr>
<tr>
<td>2000</td>
<td>0.26 0.28 0.30</td>
<td>0.39 0.43 0.46</td>
</tr>
</tbody>
</table>

From Fig14 and table: 4 (a) & (b), it is clear that the MTZ length remains constant for different impurity level and increases with mass flow according to this new developed method.

Table - 5
(a): MTZ Time (Hrs.) for Different Parameters for 1” Bed Diameter

<table>
<thead>
<tr>
<th>Inlet PPM</th>
<th>Length of Bed = 0.5m</th>
<th>Length of Bed = 1m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5g/s 1g/s 1.5g/s</td>
<td>0.5g/s 1g/s 1.5g/s</td>
</tr>
<tr>
<td>10</td>
<td>316.13 171.46 119.78</td>
<td>490.12 268.67 188.93</td>
</tr>
<tr>
<td>100</td>
<td>32.18 17.45 12.19</td>
<td>49.89 27.35 19.23</td>
</tr>
<tr>
<td>500</td>
<td>6.50 3.52 2.46</td>
<td>10.07 5.52 3.88</td>
</tr>
<tr>
<td>1000</td>
<td>3.26 1.77 1.23</td>
<td>5.05 2.77 1.95</td>
</tr>
<tr>
<td>2000</td>
<td>1.63 0.89 0.61</td>
<td>2.53 1.39 0.98</td>
</tr>
</tbody>
</table>

(b): MTZ Time (Hrs.) for Different Parameters for 2” Bed Diameter

<table>
<thead>
<tr>
<th>Inlet PPM</th>
<th>Bed Length = 0.5m</th>
<th>Bed Length = 1 m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5g/s 1g/s 1.5g/s</td>
<td>0.5g/s 1g/s 1.5g/s</td>
</tr>
<tr>
<td>10</td>
<td>1028.6 564 395.5</td>
<td>1574.3 868.7 613.5</td>
</tr>
<tr>
<td>100</td>
<td>104.7 57.4 40.3</td>
<td>160.3 88.4 62.5</td>
</tr>
<tr>
<td>500</td>
<td>21.13 11.6 8.13</td>
<td>32.35 17.9 12.61</td>
</tr>
<tr>
<td>1000</td>
<td>10.60 5.81 4.08</td>
<td>16.23 8.95 6.32</td>
</tr>
<tr>
<td>2000</td>
<td>5.32 2.91 2.04</td>
<td>8.14 4.49 3.17</td>
</tr>
</tbody>
</table>
From Fig. 15 and table: 5 (A) & (B), it is seen that MTZ time is decreasing with increase in impurity level and increase in mass flow rates. And increase with increase the bed length.

![Figure 16: Time Required to Saturate Unit Length for Different Conditions](image)

From the fig. 16 and table 6 (A) & (B), it can observe that the saturation time is gradually decreases with increase in mass flow rate and impurity level. And it do not depends on the length of the bed.

Table - 6
(a): Saturation Time (hrs.) for 1" Dia. of Adsorber Bed

<table>
<thead>
<tr>
<th>Inlet PPM</th>
<th>1&quot;Dia, 0.5m Length</th>
<th>1&quot;Dia, 1m Length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5g/s</td>
<td>1g/s</td>
</tr>
<tr>
<td>10</td>
<td>516.58</td>
<td>258.29</td>
</tr>
<tr>
<td>100</td>
<td>52.58</td>
<td>26.29</td>
</tr>
<tr>
<td>500</td>
<td>10.61</td>
<td>5.31</td>
</tr>
<tr>
<td>1000</td>
<td>5.32</td>
<td>2.66</td>
</tr>
<tr>
<td>2000</td>
<td>2.67</td>
<td>1.33</td>
</tr>
</tbody>
</table>

Table - 6
(b): Saturation Time (hrs.) for 2" Dia. of Adsorber Bed

<table>
<thead>
<tr>
<th>Inlet PPM</th>
<th>2&quot;Dia, 0.5m Length</th>
<th>2&quot;Dia, 1m Length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5g/s</td>
<td>1g/s</td>
</tr>
<tr>
<td>10</td>
<td>2006.7</td>
<td>1003.4</td>
</tr>
<tr>
<td>100</td>
<td>204.27</td>
<td>102.13</td>
</tr>
<tr>
<td>500</td>
<td>41.23</td>
<td>20.62</td>
</tr>
<tr>
<td>1000</td>
<td>20.68</td>
<td>10.34</td>
</tr>
<tr>
<td>2000</td>
<td>10.37</td>
<td>5.18</td>
</tr>
</tbody>
</table>

From the above results, it is concluded that the Rosen Model and Axial Dispersion Model can be used only to find out the MTZ time gap to find actual breakthrough time. And it is good to have lower particle diameter of charcoal, average mass flow rate and as the impurity level increases MTZ length increases and mass of adsorbent required also increase, but MTZ Time will remain constant. If the bed length increases the MTZ time, MTZ length and mass of adsorbent required increase. As the bed diameter increases, the MTZ time increases but interstitial velocity, MTZ length & saturation length decreases.
For this case the MTZ Length of the bed will be 0.4324m & saturated bed length is 0.1097m. Therefore, total required bed length is
\[ L = L_{SAT} + L_{MTZ} \]
\[ \therefore L = 0.1097 + 0.4324 \]
\[ \therefore L = 0.5421 \text{ m} \sim 0.55 \text{m} \]

For 0.55m bed length and 0.054792m bed diameter, mass of adsorbent required is 0.389 Kg of coconut shell based charcoal. So, total minimum size of charcoal adsorber bed required is 0.3m and in this case it’s selected 1 m which is in safe zone and mass of adsorbent required for this 1m length and 0.0547m bed diameter is 0.5867Kg ~ 0.6Kg.

### D. Pressure Drop & Optimization:

From a fluid mechanical viewpoint, the most important issue is that of the pressure drop required for the liquid or the gas to flow through the column at a specified flow rate. To calculate this quantity we rely on a friction factor correlation attributed to Ergun. Other fluid mechanical issues take account of the proper distribution of the liquid across the cross-section, and developing models of the velocity profile in the liquid film around a piece of packing material so that heat/mass transfer calculations can be made. Design of packing materials to achieve uniform distribution of the fluid across the cross-section throughout the column is an important subject as well. Here, we only focus on the pressure drop issue [10].

The Ergun equation that is commonly employed is given below:

\[ f_D = \frac{150}{Re_p} + 1.75 \]  

(2)

Here, the friction, \( f_D \) factor for the packed bed, and Reynolds number, \( Re_p \) are defined as follows;

\[ f_D = \frac{\Delta p}{\frac{L}{\rho_v V_s p}} \left( \frac{\varepsilon^2}{1 - \varepsilon} \right) \]  

(3)

\[ Re_p = \frac{D_p V_s p}{(1 - e) \mu} \]  

(4)

For, different L/D ratio of the adsorber bed the variation of the pressure drop is shown into fig. 25. Here, length of the bed is 1 m & diameter of the bed is 0.054m. So, L/D ratio becomes 18.25 & for average 0.002m particle diameter its pressure drop comes around 0.27 mbar which is under limit.

Fig. 17: Pressure Drop for Different L/D Ratio
Fig. 18: Pressure Drop for constant L/D Ratio and Various Void Fraction of Charcoal Particle and Different Particle Size

Fig. 17 shows the graph of pressure drop variation for 18.25 L/D ratio, charcoal void fraction varies from 0.4 to 0.48 and different particle size. Here, maximum void fraction shows the less pressure drop, so it is advisable to choose charcoal of void 0.48. Here are some derived graphs for pressure drop is shown in Fig. 19. These graphs show how the pressure drop increases with increase in mass flow rate, superficial velocity and volume flow rate.

Fig. 19: Pressure Drop Change with Different Mass Flow Rates

For 1 g/s mass flow rate, 100 PPM impurity inlet and expecting 1 PPM impurity outlet at the end of the adsorber bed, the MTZ Length & saturated bed length and Mass of adsorbent required are as per described above but for the higher impurity level the MTZ length will increase according to method: 1. So, for being on safer side the bed Dia. & Length selected is 0.0278m & 1.5m respectively for the fabrication and experiment. Following is the dimensions of the adsorber bed shown in table. Inlet & outlet of the Adsorber is by 1/8” diameter pipe, so it is required to put two reducers to connect the bed of 1” diameter with working line.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturation Length</td>
<td>0.4259</td>
<td>m</td>
</tr>
<tr>
<td>MTZ Length</td>
<td>0.5216</td>
<td>m</td>
</tr>
<tr>
<td>MTZ Time</td>
<td>17.45</td>
<td>Hrs.</td>
</tr>
<tr>
<td>Saturation Time</td>
<td>52.58</td>
<td>Hrs.</td>
</tr>
<tr>
<td>Internal Diameter</td>
<td>0.0278</td>
<td>m</td>
</tr>
<tr>
<td>Outer Diameter</td>
<td>0.035</td>
<td>m</td>
</tr>
<tr>
<td>Length of the Bed</td>
<td>1.5</td>
<td>m</td>
</tr>
<tr>
<td>Thickness of Charcoal Supporting Disk</td>
<td>0.001</td>
<td>m</td>
</tr>
<tr>
<td>Length of Reducers</td>
<td>0.080</td>
<td>m</td>
</tr>
<tr>
<td>Mass of Coconut Shell based charcoal Required</td>
<td>0.5</td>
<td>Kg</td>
</tr>
</tbody>
</table>

Veracity of the both methods will be checked during experiment and the all the dimensions will be negotiated according to availability.
III. THREE STREAM TUBE-IN-TUBE HEAT EXCHANGER

Concentric type three stream-tube in tube counter flow heat exchanger is used to achieve 20K from 300K of Helium gas which will supply with mass flow rate of 1 g/s & provided with vacuum jacket or glass wool insulation. There are too many heat exchangers available in the market which may be more effective then tube in tube heat exchanger; but tube in tube heat exchanger will provide the flexibility and reliability in fabrication & consume less time for fabrication. The diameters of the three tubes are selected based on the ease of the fabrication standpoint of 1/8”, 1/2” & 1” pipes of SS 304L. These diameters selected with consideration of sufficient gaps of >6.5mm in between tubes to pass the gas and for comfort of its development.

Fig. 20: Concentric Three Stream Tube in tube Heat Exchanger [12]

Fig. 21: Flow Pattern of Tube in Tube Heat Exchanger

Fig. 21 shows the flow pattern of fluids in the three stream tube in tube heat exchanger. The inner annular tube carry the impure helium stream at 300K and reduce its temperature to 20K by using cold helium at 4.2K & 1.3 bar in most outer annular stream. And most inner tube carry the return stream of the pure helium gas from the adsorber bed which is considered at 25K. This heat exchanger will be provided with Vacuum jacket insulation or Glass wool insulation. With the consideration of the 4.2K Liquid helium supplied with the 1.3 bar pressure to the outer annular tube, then the length of the total heat exchanger comes 2.13m out of which helium flow in liquid phase is in 0.269m length. Here, it is considered, heat transfer occurs through inner annular is 50-50% to both side. There are three streams of heat exchanger, heat transfer occurs from the inner annular to most outer annular and most inner tube. Here, it is analysed in Ansys software and concluded that 62% of heat is transferred from inner annular to most outer annular and remaining heat transfer to most inner tube of return helium stream. So, by considering 60% heat transfer to most outer annular & 40% heat transferred to most inner annular, then the length of the heat exchanger comes 2.02m. But for being on safe side the length of heat exchanger is chosen 2.13m by considering 50-50% heat hear transfer rate to both of the tube sides.

Length of the heat exchanger is 2.13m & to make it practically possible, it is provided with the U-bends in it. And for being on safe side & to reduce the drawbacks of the bends the length of heat exchanger is taken 3m. The schematic of the heat exchanger is shown into fig. 22.
A. Pressure Drop & Optimization:

In tube in tube heat exchanger, pressure drop can be calculated by following equation:

$$\Delta P = \frac{f_l v^2}{2 \rho d}$$  \hspace{1cm} (11)

And the pressure drop in the bends can calculated by [13]:

$$\Delta P = \frac{1}{2} \rho u^2 \frac{\pi R_b}{D} \frac{\theta}{180^\circ} + \frac{1}{2} \rho u^2$$  \hspace{1cm} (12)

This equation is used for finding pressure drop in bends with single phase flow in the heat exchanger. From the fig. 25, it is clear that there are total 6 bends in the heat exchanger with 180° bend. The pressure drops in all the three streams are given below in table: 5 for different mass flow rates of hot stream helium at 300K and of cold helium at 4.2K.

<table>
<thead>
<tr>
<th>Mass flow rate of hot stream, mh (g/s)</th>
<th>LHe mass flow rate, mc (g/s)</th>
<th>Total Length of HX (m)</th>
<th>$\Delta P$ in inner annular (mbar)</th>
<th>$\Delta P$ in most inner tube (mbar)</th>
<th>$\Delta P$ in outer annular (mbar)</th>
<th>$\Delta P$ in six Bends (mbar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>2.6839</td>
<td>3.726</td>
<td>12.08</td>
<td>6.881</td>
<td>0.966</td>
</tr>
<tr>
<td>2</td>
<td>2.1372</td>
<td>2.967</td>
<td>9.619</td>
<td>8.305</td>
<td>0.966</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.6845</td>
<td>2.33</td>
<td>7.58</td>
<td>8.72</td>
<td>0.966</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.5747</td>
<td>2.18</td>
<td>7.08</td>
<td>10.21</td>
<td>0.966</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5.9337</td>
<td>26.5658</td>
<td>89.85</td>
<td>33.97</td>
<td>3.5915</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2.9814</td>
<td>13.3477</td>
<td>45.1446</td>
<td>24.5638</td>
<td>3.5915</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2.4545</td>
<td>10.9888</td>
<td>37.1658</td>
<td>26.0102</td>
<td>3.5915</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2.4862</td>
<td>11.13</td>
<td>37.64</td>
<td>32.06</td>
<td>3.5915</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>4.3769</td>
<td>39.259</td>
<td>135.642</td>
<td>56.789</td>
<td>7.85</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3.2698</td>
<td>29.32</td>
<td>101.33</td>
<td>53.88</td>
<td>7.85</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2.83107</td>
<td>25.39</td>
<td>87.73</td>
<td>56.011</td>
<td>7.85</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 23: Variation in Length of Heat exchanger with Different Mass Flow Rate

Fig. 24: Pressure Drop Variation in Inner Annular tube for Different Mass Flow Rate

Fig. 25: Pressure Drop Variation in Most Inner Tube with Different Mass Flow Rate
Fig. 23 shows the variation in the length of the heat exchanger as the mass flow rate of the helium streams changes. As mass flow rate of the hot stream increases the length of the heat exchanger is increases so it is better to go for small mass flow rate that’s why 1 g/s is selected. And as the mass flow rate of the LHe increases the length is decreases. But to increase the mass flow rate of LHe might be costly for this test facility of prototype. Though it can be selected 2 g/s mass flow rate because 1 g/s flow rate increases the length of the heat exchanger and 3 g/s & 4 g/s mass flow rate increases the pressure drop in all the streams as shown in table: 5 and in fig. 24- 26. Fig. 24-26 indicate the variation of the pressure drop in different lines with respect to different mass flow rates of the fluids.

The other possibility is to take the cold stream of 4.2K LHe in most inner tube and outer stream will be of 25K return stream from adsorber bed. This arrangement can reduce the length of the heat exchanger but it increases the pressure drop very high which is not preferable.

From all the above discussion and results, the data optimized and it is concluded that mass flow rate of the hot stream heat exchanger of 300K should be 1 g/s and 4.2K cold liquid helium should be supply with 2 g/s mass flow rate.

Fig. 27 shows the simple process instrumentation diagram of the adsorber bed test facility.

**IV. CONCLUSION**

The current work deals with the design and optimization of adsorption based helium purification system at 20K and its test facility. In context to the design requirements it can be concluded that activated carbon especially coconut shell based seems to be more effective as compared to the different adsorbents discussed. In addition to this, calculation gives us for 1 m bed length and 0.0278m bed diameter, mass of adsorbent required is approximately 0.350 Kg of coconut shell based charcoal. So, total
minimum size of charcoal adsorber bed required is 1 m and in this case, it is selected 1.5 m which is in safe zone and mass of adsorbent required for that 0.5 Kg.

For the Filter Element, 550 mesh size required to prevent to enter the charcoal particles into pure helium gas of greater than 20 micron size. Optimized height and width of the mesh is 0.04m and 0.085m respectively.

For tube-in-tube three stream heat exchanger, the optimized length is 3m with 1 g/s mass flow rate of 300K hot helium stream & 2 g/s mass flow rate of 4.2K liquid helium stream which gives pressure drop within limit.

Fabrication work is in process on of this test facility at IPR site and in future, we are going to perform its testing with different adsorbents like activated charcoals and coal based charcoals to check Hydrogen adsorption capacity on those adsorbents at 20K. Selection of parameters will be negotiated during fabrication & experiment time with the consideration of other factors and availability point of view and veracity of both the methods will be check during experimental work.

ACKNOWLEDGEMENT

It is with deeply pride and pleasure to express my sincere gratitude to my guides Mr. A. K. Sahu and Prof. J. M. Patel, for their encouragement and constant help. I am obliged to the Principal and Head of the Mechanical Engineering Department of L.D. College of Engineering Ahmedabad, for giving permission to do work at Institute for Plasma research (IPR), Gandhinagar, and making available various facilities of college and department. I am also thankful to The Chairman of IPR & BRFST, for providing me such a good opportunity to do project work at IPR. I am glad to express my thanks to the entire Staff of IPR, Bhat; & Faculty Members of Cryogenic Engineering Dept. of L. D. College of Engineering, Ahmedabad for giving me the necessary guidance in the project.

REFERENCES

[13] Bends, Flow And Pressure Drop In; Jayanti & Sreenivas; http://www.thermopedia.com/content/577/