Design and theoretical analysis of Helium Purification System Components for NSRRC Cryogenic System

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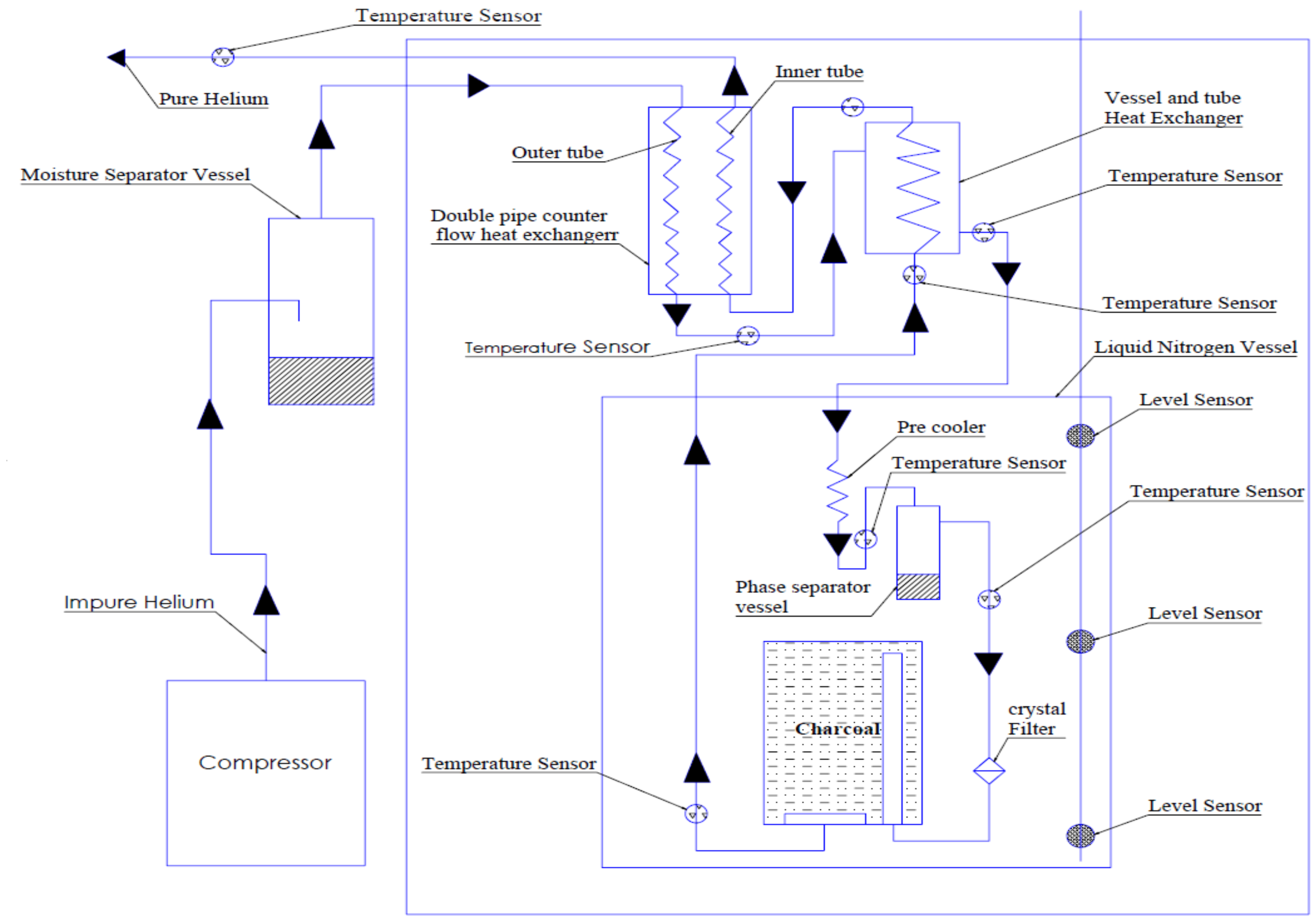
P.S. Chuang[1], H.H. Tsai, H.W. Chiang[2], F.Z. Hsiao, H.C. Li, W.R. Liao, W.S. Chiou, S.H. Chang.

National Synchrotron Radiation Research Centre, 101 Hsin-Ann Road, Hsinchu, 30076, Taiwan, R.O.C
E-mail: chuang.phd@nsrrc.org.tw

Abstract

Helium is an expensive consumable in cryogenic facilities and is used widely in space, medical and energy research. In NSRRC, liquid helium is used as a coolant for cooling superconducting magnets and SRF cavities [1]. Minor contaminants such as nitrogen, oxygen, moisture and oil will be picked up when liquid helium circulates in the large scale cryogenic systems, these contaminants will crystalize and might cause some damage in the cold box turbo expanders resulting in efficiency decay [2]. Therefore, a helium purification system is designed as an integral part of the cryogenic system to conserve helium gas by providing 99.9995% pure helium to liquefier after separating contaminants from impure helium. The NSRRC helium purification process is based on two principles, the first one is cryosorption using activated charcoal and molecular sieve and the other is cryocondensation using tubular heat exchangers. The purifier has been designed for purifying impure helium with contaminants of 2.5% nitrogen and 2.5% of oxygen with mass flow rate of 475 nm3/hr and delivering pressure of 17 bar(a) of impure helium to purifier. In this paper, calculation and design of the helium purification system and components composed of one double pipe counter flow heat exchanger, one vessel and tube heat exchanger, one pre-cooler, one charcoal vessel, mass requirement calculation of charcoal and design of other components will be discussed.

Piping and instrumentation diagram (P&ID)



Introduction

Helium is a rare gas that is widely used in different kinds of research applications such as medical, energy and space research, the consumption rate of helium usage is increasing around 10 percent every year. In NSRRC, helium is liquefied and is used as a coolant for SRF system and cryogenic undulators, when undergoing a cryogenic cycle in the cryogenic system, helium may pick up contaminants such as moisture, oxygen, oil, and nitrogen, these contaminants have a higher freezing point than liquid helium and will crystalize. These frozen impurities will then affect plant capacity and operation such as alternating flow characteristics, damaging moving parts like turbines in the coldbox causing the overall cooling efficiency to drop. Eliminating the contaminants is therefore very important for the cryogenic system.

The Helium Purifier for NSRRC is split into two major parts, the first part is to remove any excess moisture and the second to remove nitrogen, oxygen and oil. To remove moisture, a moisture separation vessel filled with Molecular sieve is designed, the moisture separation vessel at 300K will remove most of the moisture in the system, other part such as the vessel and tube heat exchanger and the crystal filter will remove the remaining moisture ice crystals. Nitrogen, oxygen and oil contaminants are removed by carbon at 80K, the carbon that is used is coconut shell.

Pressure Drop

Pressure drop of NSRRC purifier within packed bed containing particles is calculated as 62.333 x 10−5 bar by using Ergun Equation as follows

$$\mathrm{f_p} = \frac{150}{\mathrm{Gr_p}} + 1.75$$

Where $\mathrm{f_p}$ and $\mathrm{Gr_p}$ are defined as

$$\mathrm{f_p} = \frac{\Delta p}{L}\frac{D_p}{\rho v_s^2}\left(\frac{\epsilon^3}{1-\epsilon}\right)$$

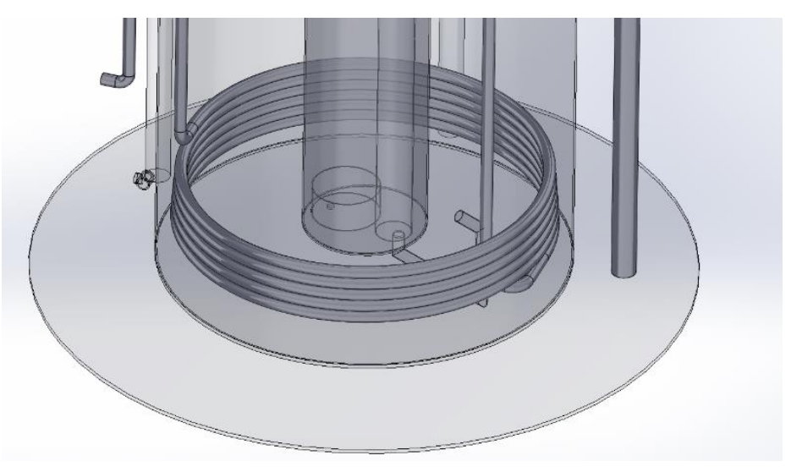
$$\mathrm{Gr_p} = \frac{\rho v_s D_p}{(1-\epsilon)\mu}$$

Where $\mathrm{Gr_p}$ is the modified Reynolds number, $\mathrm{f_p}$is the packed bed friction factor, Δp is the pressure drop across the bed, L is the length of the bed, D_p is the equivalent spherical diameter of the packing, ρ is the density of fluid, μ is the dynamic viscosity of the fluid, v_s is the superficial velocity and ϵ is the void fraction of the bed. It is evident from Ergun equation that the pressure drop within carbon vessel is 62.333 x10−5 bar, which is not significant in comparison with system pressure.

Design of Pre-cooler

The pre-cooler of the NSRRC purifier is placed between the LN2 Vessel and the carbon vessel, it is fully submerged in liquid nitrogen. The purpose of the pre-cooler is to cool helium gas to 80K before entering the carbon bed as shown in Figure 3.

To find the length L and diameter D of the copper tubing for the heat exchanger, some assumptions need to be made as follows, Ts is a constant at 77 K , helium gas (Cp= 5.2 kJ/kg K; μ= 15 x 10-6Pa s; ρ= 0.3 kg/m3, k = 0.1 W/m K), allowed pressure drop, Δp= 10 kPa, helium mass flow rate = 15 g/s.
Total heat transfer Q of 17160W and log mean temperature ΔTlm of 51K is calculated by using the equations below.



$$Q = \dot{m}Cp(Tin\text{-}Tout)$$

$$\Delta T_{lm} = \frac{\Delta T_f(x=0) - \Delta T_f(x=L)}{\ln\left(\frac{\Delta T_f(x=0)}{\Delta T_f(x=L)}\right)} \quad (1)$$

Where

$$UA = h\pi DL = Q\Delta Tlm = 336.5\ W/K \quad (2)$$

The heat transfer coefficient is a function of ReD and Pr = 0.67
Assuming the flow is turbulent and fully developed, use the Dittus Boelter correlation

$$NU_D = \frac{hD}{K_f} = 0.023{Re_D}^{0.8}Pr^{0.3}$$

$$Re_D = \frac{4\dot{m}}{\pi D\mu}$$

Substituting the ReD and solving for h

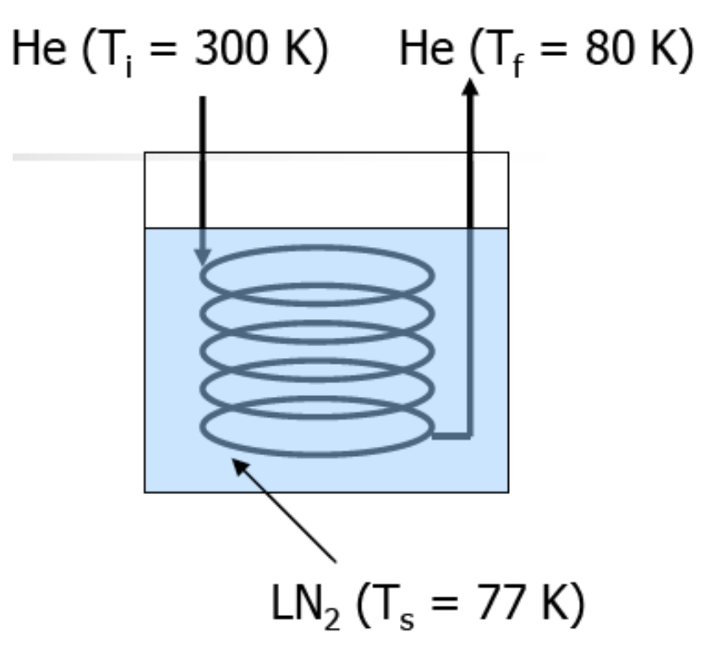
$$h = 0.023\frac{K_f}{D}\left(\frac{4\dot{m}}{\pi D\mu}\right)^{0.8} Pr^{0.3} = \frac{0.63}{D(m)^{1.8}} \quad (3)$$

Substituting equation (2) and (3), equation (4) may be calculated as shown below.

$$\frac{L}{D^{0.8}} = 169.95m \quad (4)$$

Pressure drop equation provides the other equation for L and D

$$\Delta P = f\frac{L}{2\rho D}\left(\frac{\dot{m}}{A_{flow}}\right)^2 m$$



Where $A_{flow} = \frac{\pi D^2}{4}$ and f~0.02, Substituting for ReD and f

$$\Delta P = 0.016\frac{\dot{m}^2}{\rho}\frac{L}{D^5} = 1.2 \times 10^{-5}\left(\frac{L}{D^5}\right) \quad (5)$$

Substitute equation (4) (5) with Δp = 10,000 Pa, we can calculate that D is 0.026m and L is 9.17m.

Design of Double Pipe Counter-Flow Heat Exchanger

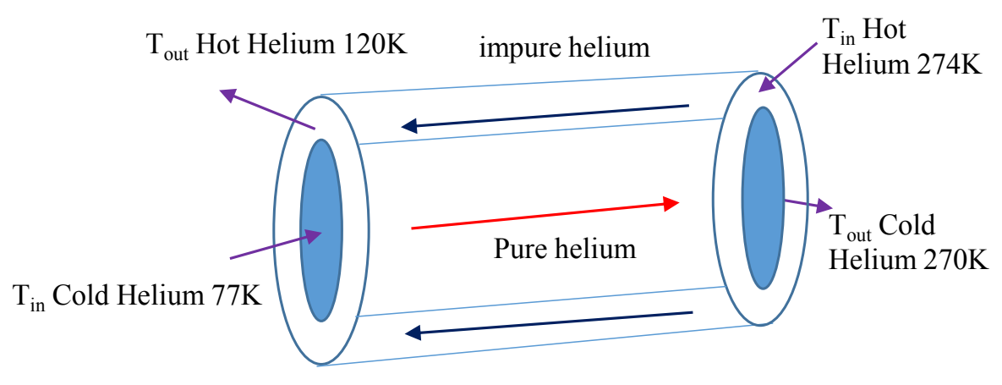
Double pipe counter flow heat exchanger is designed to cool impure helium from 300 K to 120 K and to heat pure helium from 77 K to 300K.

To calculate the length of the Double pipe counter flow heat exchanger, equation (3) is used. From the previous section, the 26mm diameter pipe has been selected for the outer pipe, a 17mm diameter pipe is selected for the inner pipe, using the same diameter pipe and substituting in equation (3), h is calculated as 449.2 W/m2 K, the overall heat transfer coefficient can be calculated as 224.6 W/m2 K using the equation below. ΔTlm is calculated using equation (1).

$$U = \left(\frac{1}{h} + \frac{1}{h}\right)^{-1}$$

The length of the double pipe counter flow heat exchanger can be calculated by substituting q, U, D and ΔTlm in equation (6), which is 77m.

$$L = \frac{\dot{q}}{U\pi D\Delta T_{lm}} \quad (6)$$



Mass Requirement of Carbon

Assume maximum impurity of helium gas is 2.5% of nitrogen and 2.5% of oxygen. Saturation pressure of nitrogen is 1 bar and oxygen is 0.2 bar at 77 K. According to Raoults's law, partial vapor pressure of each component of an ideal mixture of liquids is equal to the vapor pressure of the pure component multiplied by its mole fraction in the mixture given by

$$p = Px$$

where p is the partial pressure of a gas, P is the saturated pressure of the same gas at the same temperature and volume and x is the mole fraction. Partial pressure of air at 77K before entering the carbon bed will be

$$p_{air} = p_{O_2} + p_{N_2}$$

Due to Minimum adsorption pressure p_{min} of purifier is 17bar(a), thus Mole fraction of air X_{air} at 77k could be calculated by

$$X_{air} = \frac{p_{air}}{p_{min}} \times 100$$

Quantity of nitrogen D_{N2} to be adsorbed could be calculated by

$$D_{N2} = X_{air} \cdot Q \cdot t$$

Where Q is flow rate (475 nm3/h) and t is time (6hrs), D_{N2} could be calculated as V_a=5.03 x 10^6 cc. To calculate the mass of carbon needed, BET theory is used [5], BET equation are show as follows

$$\frac{V_a}{m_a} = \frac{\upsilon_m cx}{1-x}\left[\frac{1-(n+1)x^n + nx^{n+1}}{1+(c-1)x + cx^{n+1}}\right]$$

Where V_a = the total gas volume adsorbed at the standard state (T=273.15 K and P=101.3 kPa), m_a = mass of adsorbent, υ_m = gas volume at the monolayer coverage, p = partial pressure of the gas being adsorbed, p_{sat} = saturation pressure of the gas being adsorbed at the temperature of the adsorbent, n is the number of layer, $x = \frac{p}{p_{sat}}$ =17 and $c = \exp\left(\frac{\theta_a}{T}\right) = \exp\left(\frac{300.2}{77}\right) = 49.338$.
Equation (5) is reduced to Lamgmuir equation when n = 1 as shown.

$$\frac{V_a}{m_a} = \frac{\upsilon_m c\left(\frac{p}{p_{sat}}\right)}{1 + c\left(\frac{p}{p_{sat}}\right)}$$

Therefore, mass of activated charcoal requirement $m_a$can be calculated as 27.75Kg, Suggested by Haselden [6], estimation of a dsorbent requirement is based on 70% saturation of carbon bed, therefore minimum amount of carbon required will be 39.64Kg.

Design of Carbon vessel

Operating pressure of purifier = 17 bar(a) and flow rate =4755 Nm^3/hr max. Therefore, the flow rate of helium at 17 bar(a) and 77 k is 0.0022 m^3/sec could be calculated using the equation below.

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

The dimensions of carbon bed has been designed to keep gas velocity near 10^{-2} m/sec, due to approach velocity (V_2) of gas through fixed carbon bed ranges from 10^{-2} to 1 m/sec [7]. The inner diameter of the carbon vessel could then be calculated to be 280 mm using the equation below.

$$V = (\pi/4) \times Di^2$$

So, such pipe should be selected whose inner diameter greater than 280 mm and the gas velocity through carbon bed have optimum value. The carbon vessel will be immersed in LN_2 and will be exposed to 70^o C when regeneration heating, so 316 L stainless steel is selected as carbon vessel pipe material. Let us select a 12-inch pipe, due to pressure of helium gas is 17 bar(a), according to ASME B 31.3 (1999), Process Piping, the allowable internal pressure is calculated by using the following formula:
Allowable internal pressure,

$$P = (2 \times t_{min} \times S) / [OD - (2 \times Y \times t_{min})]$$

Where, P = 17 bar or 0.246 ksi, Allowable stress, S = 16.7 ksi for SS304, Y = 0.40 for t_{min} < OD/6,
Y = {OD - (2 x t_{min})} / 2(OD - t_{min}) for t_{min} = OD/6, t_{min} = Minimum wall thickness, OD = Nominal outside diameter, Applying Eqn. (9), we get t_{min}=2.3713 mm. So, pipe of size 12" Sch 5 (OD = 323.85 mm, t = 3.96 mm) is suitable.

Length Calculation of Carbon vessel

To calculate the carbon vessel length, the density of the carbon is needed, for the carbon used in the NSRRC purifier, active charcoal with the density of 550 kg/m^3 is used, let the length of the carbon vessel be 'L' m, inside diameter of charcoal vessel (size 12" Sch 5) di = 0.31593 m, Volume of activated charcoal of mass 39.64 kg, therefore 0.9m of length can be calculated using the equation below.

$$\pi/4 \times di^2 \times L \times density = \text{Mass of activated charcoal}$$

Due to the area of 3-inch pipe in the vessel, 3.1Kg of charcoal needs to be added back, thus 1m of 12-inch pipe will be needed.

Conclusion

The helium purifier for NSRRC cryogenic system has been designed and is now under manufacturing, the purifier has been designed for purifying impure helium with contaminants of 2.5% nitrogen and 2.5% of oxygen with mass flow rate of 475 nm3/hr and delivering pressure of 17 bar(a) of impure helium to purifier. After the helium purifier is constructed, experiments will be conducted.