Chapter 6

Design of Vacuum System For Electron Beam Thermal Application

– Baibhaw Prakash

Electron beam thermal application is widely used for welding and melting purposes. The electron beam welding and melting system consists of electron beam gun column, work chamber, job handling system, high voltage power source and vacuum pumping system. For proper functioning of electron beam system vacuum is necessary requirement. The requirement of vacuum is due to the following reasons:

a. For electron beam to travel without loss of energy and maintaining its beam profile.

b. To avoid the oxidation of filament and maintain the necessary environment for beam emission.

c. To prevent high voltage discharge inside the chamber.

6.1 Basics of Vacuum Technology

In this section, fundamentals of vacuum science and technology will be discussed. Depending on the vacuum level, different kind of vacuum pumps are required. The gas flow under various vacuum levels is different and has to be treated differently for evacuation purpose. These all points are discussed in the subsections given below.

6.1.1 Vacuum

Pressures less than atmosphere are called vacuum. Depending upon the pressure vacuum is further classified as follows:

a. Rough (or Low) vacuum (R): 1 Atmosphere to 1 mbar

b. Medium (or Fine) vacuum (MV): 1 mbar to 10^{-3} mbar

c. High vacuum (HV): 10^{-3} mbar to 10^{-7} mbar

d. Ultra-high vacuum (UHV): 10^{-7} mbar to 10^{-12} mbar

e. Extreme High Vacuum (XHV): $< 10^{-12}$ mbar.

6.1.2 Flow Types in Vacuum

Depending upon the molecular interaction, mainly three different types of flow exist in vacuum namely viscous flow also known as continuum flow, transitional flow which is also known as Knudsen flow and molecular flow respectively.

a. **Viscous (or continuum) flow**

   In Viscous flow there is close molecular interaction among the molecules. Viscous force is the dominating force in this flow region. This flow exists in the rough vacuum range and medium vacuum range i.e. from atmospheric pressure to 10^{-3} mbar pressure.

b. **Molecular flow**

   In molecular flow range, the molecular interaction among the flow molecules is very insignificant. In this flow, the molecules moves almost freely without any mutual interaction [23]. The mean free path for the molecules is much larger than the dimension of the enclosing vessel. This type of flow exists in the high and ultra-high vacuum ranges when molecules can move freely, without any mutual interference (Mean free path is defined as the mean distance travelled by molecules between two consecutive collisions).

c. **Knudsen flow**

The region of flow in between viscous flow region and molecular flow region is known as Knudsen flow. This type of flow mainly exists in medium vacuum range which belongs to vacuum of 1 mbar to 10^{-3} mbar. In this flow range the mean free path is nearly equal to the diameter of the pipe.

6.1.3 Conductance

The product of pressure and volume of flow through any desired vacuum plumbing line such as elbow, pipes , nozzles, hoses, opening is called throughput. The throughput is given by

$$Q_{pV} = C(p1 - p2) = \Delta pC \tag{6.1}$$

Here $\Delta p = (p1 - p2)$ is the differential between the pressures at the inlet and outlet ends of the piping element. The proportionality factor C is the conductance.
Conductance depends upon the geometry of the plumbing line element. In rough vacuum range and medium vacuum range conductance is directly proportional to the differential pressure of the system. So conductance needs to be calculated for each pressure range. However, in high vacuum range and ultrahigh vacuum range the conductance depends only on the geometry and is independent of the pressure so it remains constant for a given geometry. An analogy can be drawn between Ohm's law in electricity and the throughput equation for the vacuum calculation. In the above Eq. (6.1) the throughput (Q_{pv}) is equivalent to current flow (I), pressure difference (Δp) is equivalent to the potential drop and reciprocal of conductance (1/C) is equivalent to resistance respectively with respect to the Ohm's law. The analogy between Ohm's law and throughput equation is shown in the table 6.1.
When the vacuum lines are connected in series as shown in the Fig. 6.1 below in analogy with the Ohm's law, the equivalent conductance is calculated by Eq. (6.2).
Since, $R = 1/C$, the following applies directly for connection in series:

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \frac{1}{C_4} \tag{6.2}$$

When the vacuum lines are connected in parallel as shown in the Fig. 6.2 in analogy with the Ohm's law, the equivalent conductance is calculated by Eq. (6.3):

$$C_{eq} = C_1 + C_2 + C_3 + C_4 \tag{6.3}$$

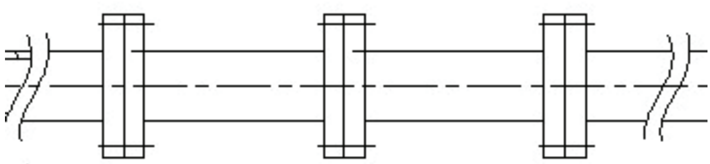

Figure 6.1: Conductance in Series.

6.2 Design of Vacuum System

The design of vacuum system is process requirement based which is need to be done in step wise manner in order to avoid the mistake and for better utilization of the resources. The basic steps involved in the design are as follows:

Table 6.1: Analogy between Ohm's Law and Throughput Equation.

Sr. No.	Ohm's Law Parameter	Throughput equation Parameter
1	Current (I)	Throughput (Q_{pv})
2	Voltage (V)	Pressure Difference (Δp)
3	Resistance (R)	Reciprocal of Conductance (1/C)

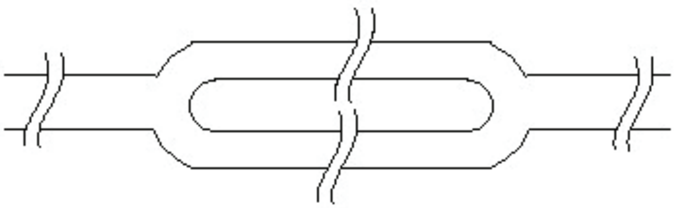

Figure 6.2: Conductance in Parallel.

a. Material Selection;

b. Vacuum Plumbing Line Design;

c. Pump and Gauge Selection.

6.2.1 Material Selection

The material with low out gassing rate is material of choice for the vacuum system. However, requirement get stringent with the level of vacuum required. Material which absorbed water vapour on its surface, material having porosity or cracks and material which sublimate are avoided. Material used should have adequate strength, maintain their properties through the entire temperature range, ease of fabrication, and should be economical. Materials like Zinc, Cadmium, Magnesium, PVC, Paints, Lead and Antimony should be avoided inside the vacuum system. Austenitic stainless steels is most commonly used for the high vacuum and ultra high vacuum system. Table 6.2 shows the outgassing rate for some commonly used materials in vacuum.

6.2.2 Vacuum Plumbing Line Design

The plumbing line for the system is designed taking in account the space available, backing pump requirement, number of pump, gauges and valves required and process requirement of the system. The pumping line is optimized in such way that the line has maximum conductance for the selected configuration and at the same time it take in account all the above mentioned factors.

6.2.3 Pump and Gauge Selection

Depending upon the vacuum level required, frequency of operation, process environment, and working condition vacuum pump is selected. For process which require very clean environment dry rotary pumps and turbo molecular pump combination is generally used because of their oil free operation. For the process which does not have any stringent requirement then diffusion pump along with rotary vane pump is used. To measure vacuum up to medium

Table 6.2: Outgassing Rate for Some Commonly Used Materials in Vacuum.

Sr. No.	Material	Outgassing Rate (Torr lit/s.cm^2)
1	Stainless Steel	2-8 $\times 10^{-8}$
2	Aluminum	7×10^{-9}
3	Mild Steel	5×10^{-6}
6	Brass	4×10^{-6}
5	High Density Ceramic	3×10^{-9}
6	Pyrex	8×10^{-9}

vacuum range pirani gauge is used and for high and ultra high vacuum penning gauge is used.

6.3 Design of Vacuum System for the 10 kW EB Melter System

6.3.1 Material Selection

The major amount of material used for the fabrication of gun column and vacuum chamber is SS304l. However, where ever required as per the process requirement other material is also used but the vacuum compatibility of the material is also taken in account. For example heat shield for the chamber is SS310, the crucible is made up of copper, shroud of focussing coil is SS430 etc.

6.3.2 Vacuum Plumbing Design

The vacuum layout for the work chamber of the 10 kW system is shown in the Fig. 6.3 and the actual fabricated chamber is shown in Fig. 6.4:

6.3.3 Pump Selection

The gun chamber is evacuated with the combination of turbo and rotary dry type pump because to have oil free environment in gun in order to increase the filament life and make the system compact. The work chamber is evacuated with the help of diffusion pump and rotary pump. In order to avoid oil back streaming inside the chamber, the nitrogen gas trap is also attached in the vacuum plumbing line.

c.1. Pump Selection For The Gun Column

In order to select the pump, we have to calculate the vacuum load. For vacuum load calculation, we have to calculate the surface area and volume of the components.

c.1.1. Vacuum Pipe for Turbo

ID of the Pipe, $d = 78.0$ mm
Length of the Pipe, $l = 90 + 99 + 139 + 53 = 381.0$ mm
Surface Area $= \pi \times\ d \times\ l = 3.14 \times 78 \times 381 = 93314.52$ mm^2
Volume of the pipe $= (\pi \times\ d^2 \times\ l)/4 = 1819633.14$ mm^3

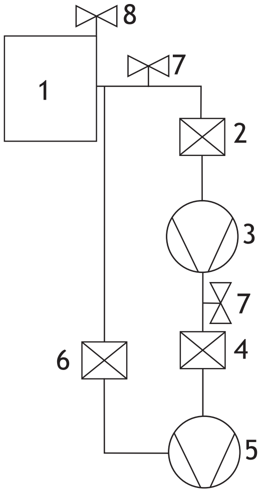

Figure 6.3: Vacuum Layout of work chamber for the 10 kW EB Melter: 1. Work Chamber, 2. Right Angle Valve, 3. Diffusion Pump, 4. Backing Valve, 5. Roughing and Backing Rotary Pump, 6. Roughing Valve, 7. Pirani Gauge, and 8. Penning gauge.

Figure 6.4: Photograph of Vacuum Plumbing Line for 10 kW System.

c.1.2. Gun Chamber

ID of Gun Chamber, $d = 186.0$ mm

Length of the Chamber, $l = 162.3$ mm

Surface Area $= \pi \times d \times l = 3.14 \times 186 \times 162.3 = 94789.69$ mm^2

Surface Area of Top and bottom $= (2 \times \pi \times d^2)/4 = 2 \times 27157.86 = 54315.72$ mm^2

Volume of the pipe $= (\pi \times d^2 \times l)/4 = 4407720.678$ mm^3

c.1.3. Vacuum Port Gun Chamber

ID of the Pipe, $d = 78.0$ mm

Length of the Pipe, $l = 63.0$ mm

Surface Area $= \pi \times d \times l = 3.14 \times 78 \times 63 = 15429.96$ mm^2

Volume of the pipe $= (\pi \times d^2 \times l)/4 = 300884.22$ mm^3

c.1.4. Focussing Lens Chamber

ID of the Focus Chamber, d	: 47.0 mm
Length of the Chamber, l	: 236.0 mm
Surface Area, $\pi \times d \times l$	: $3.14 \times 47 \times 236 = 34828.88$ mm^2
Volume of the pipe, $\frac{\pi \times d^2 \times l}{4}$	: 409239.34 mm^3

c.1.5. Gate Valve Region

ID of the Gate Valve, d	: 100.0 mm
Length of the Chamber, l	: 72.0 mm
Surface Area, $\pi \times d \times l$	: $3.14 \times 100 \times 72 = 22608$ mm^2
Surface Area of Valve Plate Top and bottom Side, $\frac{2\times\pi\times d^2}{4}$	: $2 \times 7850 = 15700$ mm^2
Volume of the pipe, $(\pi \times d^2 \times l)/4$	: 565200 mm^3

c.1.6. Oscillation and Deflection Regions

ID of the Pipe, d	: 60.0 mm
Length of the Chamber, l	: 96.0 mm
Surface Area, $\pi \times d \times l$	: $3.14 \times 60 \times 96 = 18086.4$ mm^2
Volume of the pipe, $(\pi \times d^2 \times l)/4$	: 271296 mm^3
Total surface Area of the Gun Chamber	: 349073.172 mm^2
Total Surface Area of SS304L	: 321915.312 mm^2
Total Surface Area of Cu	: 27157.86 mm^2
Total Volume of the Gun Chamber	: 7773973.378 mm^3
Total Volume of the Chamber in Lit.	: 7.77
Out Gassing Rate of SS304L	: 2.5 to 4×10^{-8} Torr lit/sec.cm^2
Out Gassing Rate of Copper	: 7×10^{-7} to 2×10^{-7} Torr lit/sec.cm^2
Load Due To Out Gassing	: 35×10^{-7} Torr lit/sec
Load Due To Gas Generation	: 50×10^{-6} Torr lit/sec
Total Throughput, Q_{total}	: 53.5×10^{-6} Torr lit/sec

Using the equation, $S = Q_{total} / P_u$
$\Rightarrow P_u = 1 \times 10^{-6}$ mbar $= 0.75 \times 10^{-6}$ torr.
$\Rightarrow S = (53.5 \times 10^{-6}) / (0.75 \times 10^{-6}) = 71.33$ lit/sec
Conductance, $C = 12.1 \frac{d^3}{L_{eq}}$
For the plumbing line the effective conductance, $C_{eq} = 97.65$ lit/sec
Using the equation, $\frac{1}{S} = \frac{1}{S_p} + \frac{1}{C_{eq}}$
$\Rightarrow 1/71.33 = 1/S_p + 1/97.65$
On solving we get, $S_p = 262.10$ lit/sec.
Hence, for the Gun Column Assembly 300 Lps turbomolecular pump is selected.

c.2. Pump Selection for the Work Chamber

Surface Area and Volume Calculation Work Chamber
Inside Dimension of the Chamber (H × B × L) = 450 mm × 460 mm × 482 mm
Surface Area of the Chamber Inner Wall = 2(L × B + B × H + H × L) = 1291240 mm^2
Total Surface Area of The Chamber Including Shield = 3873720 mm^2 = 38738 cm^2
Out Gassing Rate = 155×10^{-5} Torr lit/sec
Load Due to Gas Generation = 124.5×10^{-5} Torr lit/sec
Total Vacuum Load = 280×10^{-5} Torr lit/sec
Conductance, $C_{eq} = 500$ lit/sec
Using the equation, $\frac{1}{S} = \frac{1}{S_p} + \frac{1}{C_{eq}}$,
and $S = Q_{total} / P_u$, we get,
$P_u = 1 \times 10^{-5}$ mbar $= 0.75 \times 10^{-5}$ torr.
$\Rightarrow S = 372$ lit/sec.
$\Rightarrow S_p = 1453.125$ lit/sec.
Nearest Suitable Pump is Agilent VHS-6.

Questions

1. Why Vacuum is required for Electron Beam Operation?
2. State desirable property of material for Vacuum System?
3. What are different types of flow in Vacuum?
4. What is vacuum and its classification?

Answers

1. The vacuum is required for the electron beam operation due to the following reasons
   a. For electron beam to travel without loss of energy and maintaining its beam profile.
   b. To avoid the oxidation of filament and maintain the necessary environment for beam emission.
   c. To prevent high voltage discharge inside the emitter assembly.
2. The material should have low out gassing rate, ease of machine ability, easily weld able, economical and ease of availability in market.
3. There are three types of flow in vacuum namely viscous flow, Knudsen flow and Molecular flow.
4. Pressure less than atmosphere is called vacuum. It is classified on the basis of vacuum range in the chamber.

Suggestions for Further Reading

a) [23–25]