**Learning Activity 8: Rough Vacuum System Pump-Down Time**

**Summary of Learning Activity:**

* Measuring physical parameters of the vacuum system to determine the volume of gas inside the chamber and vacuum piping.
* Using technical specification sheets to identify operational information for the rough vacuum pump such as its ultimate pressure and pumping speed curves.
* Calculating pump-down time using the pump’s pumping speed.
* Calculating the series conductance of the vacuum piping components.
* Determining the effective pumping speed using the pump’s pumping speed and the series conductance of vacuum piping components.
* Calculating pump-down time using effective pumping speed and experimentally verifying its accuracy.

# Student Learning Objectives:

1. Use a vacuum pump’s technical specification sheet to identify operational parameters.
2. Measure the dimensions of a rough vacuum system.
3. Estimate/calculate pump-down time for a rough vacuum system.
4. Practice unit conversion calculations.
5. Calculate the conductance of various vacuum piping components and their effect on the system’s pumping speed.
6. Verify estimated pump-down times experimentally.
7. Practice organizing data and results using a table format.

**Suggested Pre-lab Assignment:**

1. Review Examples 4.6, 4.7, 4.10 and 4.11 in Chapter 4.
2. Calculate the Knudsen number for a system operating at 10 Torr under room temperature conditions and with an internal pipe diameter of 4.0 cm. Use Equation 8.6 in the theoretical section. Determine whether the flow is viscous or molecular.
3. Calculate the Knudsen number for a system operating at 5 x 10-5 Torr under room temperature conditions and with an internal pipe diameter of 4.0 cm. Determine whether the flow is viscous or molecular.

**Theoretical Background:**

For pressures above 10-2 Torr, the volume of the chamber and the effective pumping speed are the determining factors when calculating pump-down times. If a chamber with volume *V* is connected directly to a pump, then the effective pumping speed is essentially equal to the pump’s pumping speed. The ultimate pressure of the pump is specified as and represents the lowest pressure attainable with this pump. At time *t* = 0, the initial pressure shall be given by . The pump-down time from to some final pressure is given by the following equation, assuming that the chamber is clean and does not have any leaks:

(Eq. 8.1)

Vacuum chambers are typically shaped as cylinder, sphere, or some combination of both. Thus, the following expressions are useful to calculate the volume of the chamber. The volume of the cylinder is calculated using Equation 8.2:  
  
  (Eq. 8.2)  
  
where *D* is the inside diameter (ID) of the cylindrical chamber, and L is its length. The same expression can be used to calculate volume of cylindrically shaped vacuum piping components.  
  
The volume of the sphere is calculated using Equation 8.3:  
  
 (Eq. 8.3)  
  
where *D* is the inside diameter (ID) of the sphere.

See Example 4.9 in Chapter 4 of the EBook “Introduction to Vacuum Technology” for an example addressing the detailed calculations of the pump-down time.  
  
Equation 8.1 above assumes that the conductance of the connection between the pump and the chamber is much greater than the pumping speed of the pump. When this is not the case, then the conductances of vacuum piping components need to be calculated and used to determine the effective pumping speed.   
  
The conductance of a straight pipe, or tube operating in the viscous flow range, is given by:  
  
 , (Eq. 8.4)  
  
where   
 *Ct* is the conductance in liters per second,   
 *D* is the inside diameter of the pipe in centimeters,   
 *L* is the length of the pipe in centimeters, and  
 *pave is the average pressure in the pipe in torr,* with *p1* being the pressure at the start of the pipe (along the direction of flow) and *p2* being   
 the pressure at the end of the pipe.

Conductance of the aperture, where the gas enters the pipe from the chamber, also needs to be accounted for. For viscous flow, the conductance of the aperture can be calculated using Equation 8.5:  
  
 (Eq. 8.5)  
  
where   
  
 *Ca* is the conductance of the aperture in liters per second,  
 *A* is the cross-sectional area of the aperture in cm2, and  
 is the ratio of the pressure in the pipe divided by the pressure in the chamber (can be neglected   
 for viscous flow when *Pult⋅ D > 5 X 10-1 Torr-cm*).

To verify that the system is operating in the viscous flow regime, Knudsen number should be less than 0.01. Knudsen number is calculated as shown in Equation 8.6:

(Eq. 8.6)

where MFP is the mean free path in units of cm and D is the inside diameter of the piping in cm. If the temperature conditions are approximately 20oC, the rule of thumb calculation for MFP can be used: MFP = 0.005Torr-cm/P where P is the pressure in Torr.  
  
  
Since the conductance of the tube and conductance of the aperture act as series elements, and they are in series with the pump, then the net conductance of the piping and the aperture in series is determined by the following expression:  
  
 (Eq. 8.7)  
where  
 *Cnet* is the net conductance of the tube, and  
 *Ct* and *Ca* are conductances of the length of the tube and the tube’s aperture respectively.

And finally, the effective pumping speed of the system or speed at which gas is removed from the chamber can be calculated using Equation 8.8:  
 (Eq. 8.8)  
where  
 *Seff* is the effective pumping speed,  
 *Cnet* is net conductance of all tubes and aperture,   
 *Spump* is the pumping speed of the pump.  
  
Care should be taken to express all conductances and pumping speeds in the same units of measure. The unit of measure consistent with Equation 8.4 and Equation 8.5 is liters/sec. **N**ote that conductances of piping, as well as pump’s pumping speed, change with changing pressure. Thus, pump-down time calculations will only produce an *estimate* for the system’s pump-down time.

# Equipment and Materials:

1. Vacuum system consisting of:
   1. one process chamber,
   2. one absolute pressure measurement device,
   3. one vent valve,
   4. one isolation/roughing valve,
   5. vacuum piping, and
   6. one rough vacuum pump.
2. Timer
3. Pumping speed chart for the rough vacuum pump (from pump’s specs)
4. Machinist’s ruler and/or tape measure
5. Vernier calipers (recommended)

# Procedure:

**Learning Activity 8.1: Determining Volume of Rough Vacuum System**

1. Measure dimensions of all vacuum components in centimeters (chamber, piping, apertures):   
   - for cylindrical components, measure length *L* and inside diameter *D*,  
   - for spherical components, measure inside diameter *D*,  
   - for circular aperture, measure inside diameter *D*.  
   Use vernier caliper to measure inside diameter and the length of shorter pipes. Use ruler or tape measure for the rest of the measurements.   
   **Note:** If spare components of the same inside diameter are available, use them to make measurements instead of disconnecting components of the system. If you need to disconnect the system’s components, make sure that you vent the rough vacuum system first and use gloves when working with the vacuum system.
2. Record measured data in Table 8.1.
3. Calculate the inside volume of each vacuum components. You may want to assign calculations for different components to different students in each lab group to speed up the process. Work as a team!
4. Record calculated volumes in Table 8.1.
5. Calculate total volume and record in units of cm3/sec and liters/sec in Table 8.1.

# Date data recorded:

**Table 8.1. Volume Measurements and Calculation Results**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Component | Length  (cm) | Inside diameter (cm) | Radius  (cm) | Volume  (cm3) | Volume  (liters) |
| Chamber |  |  |  |  |  |
| Piping leading to roughing valve |  |  |  |  |
| Small volumes attached to the chamber (optional): |  |  |  |  |
| Piping leading to  vacuum gauge 1 |  |  |  |  |
| Piping leading to  vacuum gauge 2 |  |  |  |  |
| Piping leading to  vent valve |  |  |  |  |
| **TOTAL VOLUME** |  |  |  |  |  |

**Learning Activity 8.2: Determining Vacuum Pump’s Parameters from Pump’s Specs**

1. Identify pump’s ultimate pressure, *Pult*, and record in Table 8.2. Convert *Pult* to units of torr and record in Table 8.2.
2. Identify pump’s pumping speed, *Spump*, and record in Table 8.2. You may need to use different estimates for pumping speed in different pressure ranges if pumping speed changes substantial between initial and final pressures. See EBook Example 4.9 for more details.
3. Express pumping speed in cm3/sec and liters/sec and record in Table 8.2.

# 

**Table 8.2. Pump’s parameters Date data recorded: \_\_\_\_\_\_\_**

|  |  |
| --- | --- |
| ***Pult with units*** |  |
| ***Pult (Torr)*** |  |
| ***Spump with units*** |  |
| ***Spump (cm3/sec)*** |  |
| ***Spump (liters/sec)*** |  |

**Learning Activity 8.3: Determining Conductance of Rough Vacuum System**

1. Verify the viscous flow regime by calculating Knudsen number (Equation 8.6).
2. Measure inside diameter (in cm) and the length (in cm) of every tubing component between the chamber and the rough vacuum pump. Calculate conductance of each tubing component, ***Ct#***, using Equation 8.4 and record in Table 8.3.   
   Note: Divide conductance of each piping component by 2 for each 90 degree bend.
3. Measure the inside diameter of the piping component directly attached to the chamber. Calculate conductance of aperture, ***Cap***, using Equation 8.5 and record in Table 8.3.
4. Calculate net conductance of the system, *Cnet*, using Equation 8.7, and record in Table 8.3.
5. Calculate effective pumping speed of the rough vacuum, S*eff*, using Equation 8.8, and record in Table 8.3.  
    **Table 8.3. Conductances – Data and Calculation Results. Date data recorded:**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Component** | **Inside Diameter  (cm)** | **Length (cm)** | **Bend (Y or N)** | **Conductance  (liters/sec)** |
| Piping component 1  (Cp1) |  |  |  |  |
| Piping component 2  (Cp2) |  |  |  |  |
| Piping component 3  (Cp3) |  |  |  |  |
| Aperture (Cap) |  |  |  |  |
| **Net Conductance of Piping and Aperture (Cnet)** |  |  |  |  |
| **Effective Pumping Speed of Rough Vacuum system (Seff)** |  |  |  |  |

**Learning Activity 8.4: Estimating the Pump-Down Time**

1. Measure the initial pressure of the vented chamber, *Pi,* using an absolute pressure vacuum gauge, and record your measurements in Table 8.4 in units of torr.
2. Record the final pressure provided by the instructor, *Pf,* in Table 8.4 in units of torr.
3. Copy the ultimate pressure of the pump, *Pult,* from Table 8.2 to Table 8.4.
4. Copy the total volume from Table 8.1 to Table 8.4.
5. Copy the *Spump* and *S*eff values from table 8.3 to Table 8.4.
6. Use Equation 8.1 to calculate the estimated pump-down time (*tpump only*) using only the pump’s pumping speed.
7. Use Equation 8.1 and *Seff* to calculate the estimated pump-down time (*tpump and piping* ).
8. Calculate percent difference between pump-down times from step 17 and step 18 and record in Table 8.4.

**Table 8.4. Pump-Down Time Estimation Date data recorded: \_\_\_\_\_\_\_**

|  |  |
| --- | --- |
| ***Pi (Torr)*** |  |
| ***Pf (Torr)*** |  |
| ***Pult (Torr)*** |  |
| ***V(liters)*** |  |
| ***Spump (liters/sec)*** |  |
| ***Seff (liters/sec)*** |  |
| ***tpump only (sec)*** |  |
| ***tpump and piping (sec)*** |  |
| ***% Difference (%)*** |  |

**Learning Activity 8.5: Experimentally Verifying the Pump-Down Time**

1. Attach all components that you disconnected to take measurements.
2. Close the vent valve and the roughing valve.
3. Turn on the vacuum gauge, if applicable.
4. Start the rough vacuum pump and run for few seconds.
5. Open the roughing valve and start the timer at the same time.
6. Stop the timer when chamber pressure reaches the final pressure equal to the final pressure used in your calculations. Record the timer value as *texp In Table 8.5.*
7. Close the roughing valve.
8. Turn off the rough vacuum pump.
9. Turn off the vacuum gauge.
10. Note: You may want to repeat the pump-down because the first pump-down process may be affected by the outgassing of adsorbed water molecules.
11. Calculate the percent different between *texp* and *tpump only* and record in Table 8.5.
12. Calculate the percent different between *texp* and *tpump and piping* and record in Table 8.5.

**Table 8.5. Experimental Data Date data recorded: \_\_\_\_\_\_\_**

|  |  |
| --- | --- |
| ***texp (sec)*** |  |
| ***% Difference between texp and tpump only (%)*** |  |
| ***% Difference between texp and tpump and piping (%)*** |  |

Observation Notes: Describe how close are calculated and experimentally measured pump-down times.

**Analysis:**

Based on the percent difference between (*texp* and *tpump only*) and beween (*texp* and *tpump and piping*), which calculated value is the closest to the experimentally measured one? Why?

Did you overestimate or underestimate the pump-down time? Explain what could be the possible reasons for this.

What are the effects of conductance of the piping and conductance of the aperture on the overall net series conductance and on the pump-down time?

A blue background with black text

Description automatically generated with medium confidence