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Performance Evaluation of Vacuum System: Pump-down Time

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Abstract— Vacuum system finds applications in number of industries like process industry, pharmaceutical industry, petroleum industry, material handling industry, etc. In most of its applications it is used as vital part of the system. A suboptimal performance in vacuum system may result in inferior overall system performance. The performance of vacuum system is practically gauged in terms of time required to achieve the requisite low pressure. This time is referred as pump-down time. Among the number of factors affecting pump-down time important are pressure to be achieved and configuration of the system (length and diameter of tubing used to connect vacuum tank and pump). In this paper theoretical procedure for calculating pump-down time is explained for the given pressure and configuration of the system. These theoretical calculations are compared with the actual observations taken from the system. Graph of evacuation pressure vs time is drawn for theoretical and actual observations and it is analyzed.

Index Terms— Vacuum, vacuum pump, pump-down time, performance, conductance, pumping speed.

1 Introduction

Vacuum pump finds application in many number of industries as a vital part of the system. But very few things are known by the engineers regarding vacuum pump and vacuum system performance

Vacuum is defined as the space devoid of mater. For general sense it is considered as pressure below atmospheric pressure. Vacuum is broadly divided in the following categories

Pressure Range	Pressure in mbar
Low vacuum	10^{3} - 10^{0}
Medium vacuum	10^{0} – 10^{-3}
High vacuum	10^{-3} - 10^{-7}
Ultra high vacuum	10^{-7} – 10^{-12}

The different types of vacuum pumps are available for different pressure ranges of vacuum. Noramally the manufacturere provides the characteristics curve showing relation of pumping speed versus pressure for each vacuum pump. This characteristic curve helps to determine the pump-down time in ideal situation. Pump-down time is the time required to to achieve the required pressure.

But the characteristics curve has limitations when actual system consisting of tank to be evacuated, piping of differeent dimensions with bends, is there. In this paper theoretical analysis for finding pump-down time of a simple system is explained followed by the experimental results for the same system.

2 Theoretical Calculation for pump-down time

The theoretical analysis for punp-down time calculation for a vacuum system consists of following procedural steps:

Step 1: calculation of Knudsen Number to determine whether the flow is viscous or molecular.Knudsen number is the ratio of mean free path of molecule to the diameter of pipe. For Kn < 0.01 the flow is regarded as viscous and for Kn > 0.03 the flow is regarded as molecular.

Step 2: Conductance calculation: the pumping speed of a vacuum pumping station is reduced upto the recipient through intermediate line, components such as valves and bellows. The longer the lines and smaller the cross section, the grater are the losses.

For determination of losses, in practical applicatons, conductance C is used. In addition to length and diameter, conductance also depends upon the type of flow of pumped down material. For vacuum technology mainly viscous and molecular flow are suitable. In the range of viscous flow the conductance is dependent on pressure while in molecular flow range it is independent of pressure. The conductance for round pipes is calculated universally for all pressure ranges and for all gas types as:

$$C = \frac{3.6 * r^3}{l}\left(0.039\frac{r.p_m}{\eta} + 30\sqrt{\frac{T}{M}}\right)$$

For air the conductance is calculated as:

$$C = \frac{3.6 * r^3}{l}\left(0.039\frac{r.p_m}{\eta} + 95\right)$$

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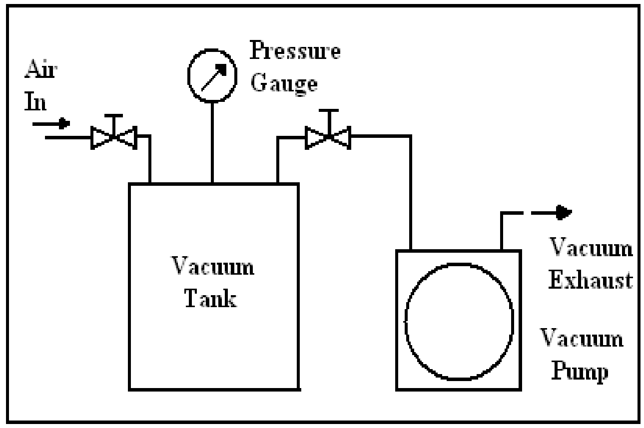


For air in the laminar flow range, the second term in the paranthesis can be omitted, yielding a simplifies formula,

$$C = 7750\frac{r^4 \cdot p_m}{l} \quad m^3/hr$$

In the molecular flow range the first term in the paranthesis can be omitted, yielding the formula for air as;

$$C = \frac{340.r^3}{l} \quad m^3/hr$$

For a system having number of valves, joints and bends, for calculating conductance equivalent length is to be considered instead of pure length of pipe.

Step 3:

Assuming mean pressure the value of effective pumping speed is calculated by the following formula:

$$S_{eff} = \frac{1}{\frac{1}{C}+\frac{1}{S}} = \frac{C.S}{C+S}$$

Step 4:

The effective pressure can be calculated using equation;

$$P = \frac{P_{Eff}.S_{eff}}{S}$$

The value of assumed pressure should match with the pressure calculated afterwards.For this purpose iteration method is to be used to find out the proper value of effective pumping speed.

Step 5:

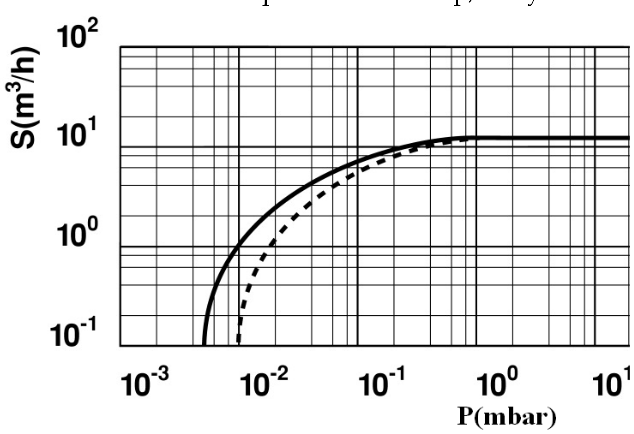
Using the value of effective pumping speed from step 4 the value of pump-down time is calculated using the formula;

$$t = \frac{V}{S_{eff}}\ln\left(\frac{P_1}{P_2}\right) \; hr$$

Using above procedures the pump-down time for a particular pump is calculated theoretically to achieve a specific pressure.

The experimental set-up for the system studied is as follows:

As shown in experimental set-up, a system is studied in which it is required to evacuate a tank of 98 litres using pump for which the rated pumping speed is 10 m^3/hr upto a pressure of 0.1 mbar. The tank is connected to the vacuum pump with standard pipe for which internal diameter is 30mm. The characteristic curve for the pump is as shown below:



$$C = \frac{3.6 * 1.5^3}{500}\left(2150 * 1.5 * 0.096 + 95\right)\ m^3/hr$$

$$C = 9.83178\ m^3/hr$$

The above characteristics curve for the pump selected indicates that pump speed of 10 m^3/hr is fairly constant for pressure upto 0.1 mbar. For pressure lower than the pressure from the curve deviates from linearity, the volume rate curve is divided in several partial pressure ranges of small volume flow rate. From this characteristics curve it is possible to calculate the pump-down time using standard pump-down time formula but in that case limitations of practical system such as configuaration of actual system are not considered.

Using the conductance formula for air, conductance is calculated. For calculating conductance the initial guess for mean pressure is taken as 0.096 mbar.

From this value of conductance , effective pumping speed is caluculated. Theoretical pumping speed is taken as 10 m^3/hr.

$$Seff = \frac{C * S}{C + S}$$

$$Seff = \frac{9.83178 * 10}{9.83178 + 10}$$

$$Seff = 4.95759\ m^3/hr$$

Then pressure is calculated as:

$$P = \frac{P_{eff} * S_{eff}}{S}$$

$$P = \frac{0.1 * 4.95759}{10}$$

$$P = 0.04958\ mbar$$

This pressure is compared with the assumed mean pressure and the error is found out. Iteration method is used to reach maximum correct value. Microsoft excel tool can be used to acieve the maximum correct value of pumping speed.

For the above given conditions using bisection method of iteration the value of effective pumping speed comes to be 4.4645 m^3/hr with an error of 1.5 %. Using this pumping speed value, the time required to evacuate tank of the given size is calculated as given below.

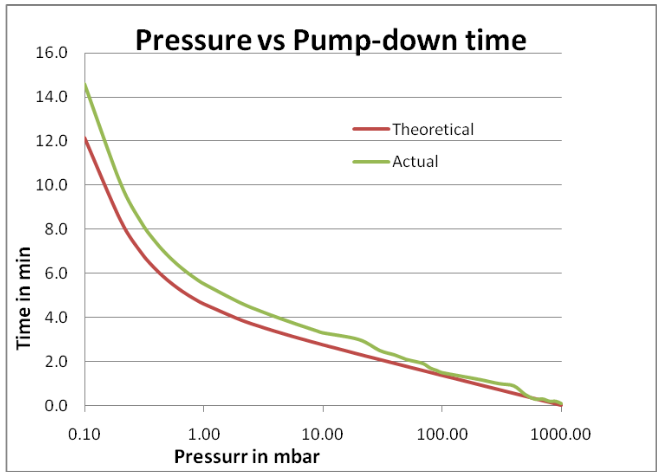
$$t = \frac{0.098}{4.4645}\ln\left(\frac{1013}{0.1}\right) * 60 \quad \min$$

$$t = 12.1 \min$$

Hence the time required to evacuate the tank of 98 litres consisting of tubing of length 5 m using the given vacuum pump is 12.1 minutes.

The calculations are repeated for pressures ranging from atmospheric pressure to the final low pressure of 0.1 mbar and graph of pressure vs pump-down time is plotted on semi-logarithmic scale.

3. Results and Discussion:



The following observations are recorded from the above graphical analysis:

1. The pumping speed varies with pressure to be achieved and system configuaration. Hence it is not advisable to calculate the evacuation time from the characteristics curve of vacuum pump alone.
2. As pressure decresres, the time required for evacuating the tank increases and this increase is more for very low pressures.
3. The variation of actual evacuation time from theoretical evacuation time may be attributed to leakages through the various joints in the sytem.

4 Conclusion:

When a vacuum system is to be designed to get a particular pressure in predecided time, pressure should not be the only criteria for selection of vacuum pump. Evacuation time also depends on length and diameter of tubing. So before installing any vacuum system proper study of overall configuaration of system with pump is necessary so that pump-down time can be optimized using proper length and diameter of tubings in the system.

5 Abbreviations:

C-Conductance in m^3/hr

S- Pumping speed for pump in m^3/hr

S_{eff} – Pumping speed at tank in m^3/hr
P_m – mean pressure in mbar
r – Radius of tubing in cm
l – Length of tubing in cm
T – Absolute temperature in K
M – Molecular mass of gas
η – Viscosity of gases in Pa-s
t – Pump-down time in min
V – Volume of tank in m^3
P_1, P_2 – Pressures at respective ends in mbar

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