OPTIMISE VACUUM TO IMPROVE PLANT PERFORMNCE

Vacuum Pumps and systems are widely used in the chemical process industry for various applications such as drying, solvent recovery, distillation, short path distillation (Molecular distillation), concentration etc. It is therefore, essential that the vacuum principles are understood which can be employed to maximize process throughputs, product purity and quality & minimize power consumption.

Success has been achieved in many industries such as food product, essential oils, aromatics, solvent recovery and steam jet replacements. Wide range of pumps and vacuum equipment is being used in the industry to achieve the desired vacuum and pumping speeds. The understanding of their advantages and limitations can result in optimizing their performance.

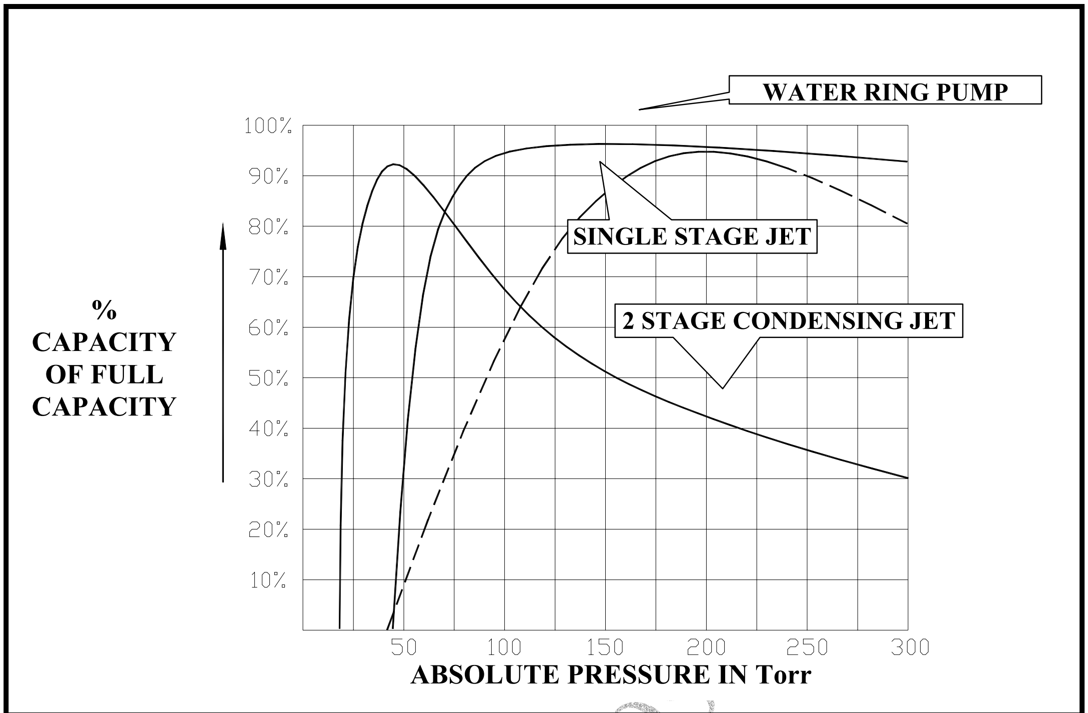
What is Vacuum?
Vacuum is simply a pressure below atmosphere. To create vacuum in a system, a pump is required to remove mass (gas/vapor) from the system. The more mass is removed, lower is the pressure that exists inside the system. Various vacuum levels are defined depending upon the ultimate vacuum as:

Range	***Absolute pressure range***
❑ Coarse Vacuum	10 – 760 Torr
❑ Medium Vacuum	0.001 – 10 Torr
❑ Fine Vacuum	10^{-3} – 10^{-7} Torr
❑ Ultra High Vacuum	< 10^{-7}

Generally, the chemical industry operates in Coarse and Medium vacuum range. In this range the vacuum is generally measured in mm Hg gauge or Torr (absolute pressure). Measurements from datum as atmosphere are gauge reading, whereas the measurements referred to absolute zero are expressed in Torr. For example at sea level (atmospheric pressure 760mmHg), a system maintained under vacuum of 700mmHg, as indicated by vacuum Boudorn gauge, is said to have absolute pressure of 60 Torr. Vacuum gauges, mercury manometers, transducers etc. indicate gauge pressure and their reading when subtracted from atmospheric pressure gives absolute pressure. It is important to under stand the above since all vacuum principles and calculations are based on absolute pressure units.

Pumping speed: It is the volumetric rate of exhausting, generally expressed in Lts/min., m^3/hr or cfm. It is the rate at which the inlet of the pump actually removes the gas / vapor load. It should not be confused with Displacement of the pump. Displacement of a pump is the geometric volume swept by the pump per unit time at rated operating speed. For most of the pumps, pumping speed is close to displacement value at no load conditions (FAD-Free air delivery) and changes with inlet pressure, reaching to zero where the pressure attained is said be pumps **ultimate pressure**. The Curve below, gives pumping speed for different type of pumps.

PUMPING SPEED VRS PRESSURE



It is evident from the curve that pumping speed drops with drop in pressure. This must be taken into consideration while selecting a pump.

The inlet pressure at which the pump's speed falls to zero is termed as "Ultimate pressure or Blank-off pressure" of the pump. It is a pump characteristic, dependent on the type of pump/ pump construction. The ultimate pressure / Blank off pressure of a pump can be easily checked by measuring the inlet pressure, with inlet of the pump blanked off. At Blank-off pressures, the effective pumping speed of the pump is zero. This means that a process can never achieve vacuum better than the blank off vacuum of the pump. While selecting a pump, desired process vacuum and that achievable by a pump must be verified. Ultimate vacuum is the pump type characteristic and general conception that using a bigger Pump (of the same type) would yield better vacuum is false. The process engineer's should establish desired process vacuum and the selection of the pump should be made accordingly. To get better working vacuum and higher pumping speed, Boosters are invariably used in combination. In most cases much higher speed and lower pressure can be achieved with a fraction of extra power, when Booster combination is used.

The table below gives an approximate idea of how booster combination can yield lower pressures while maintaining high pumping speeds.

Vacuum Pump	Pressure Range	Pressure range with Booster combination
Single Stage Ejector	**150 Torr**	**15 – 30 Torr**
Water Ejector	**100 Torr**	**10 – 20 Torr**
Water Ring Pump	**40 – 60 Torr**	**5 – 10 Torr**
Liquid Ring Pump	**20 – 30 Torr**	**2 – 5 Torr**
Piston Pumps	**20 – 30 Torr**	**2 – 5 Torr**
Rotary Piston Pumps	**0.1 Torr**	**0.01 Torr**
Rotary Vane Oil Pump	**0.01 – 0.001 Torr**	**0.001 – 0.0001 Torr.**

The most important parameter effecting the vacuum pump selection is the suction pressure that must be reached or maintained and throughput the pump must handle. Pumping characteristics for the pump selected are of prime importance as most of the pumps have a working pressure range where they are most efficient and below which their performance drops considerably. The process working pressure and load are the major factors governing the pump selection.

Invariably, the process demand of higher working vacuums ends up in installation of higher capacity pump adding to considerable capital & working costs with little or no gain in vacuum. For example if a process demands system pressures to be maintained at 50 Torr (710mmHg) with non condensable load of 10 Kg/hr at 30^{O}C, ideal pump should have a capacity of 130 m^3/hr at 50 Torr. Use of water ring pump which has it's ultimate at 710mmHg would be a wrong choice. A Booster and Water ring combination would be the most energy efficient choice.

Estimating pumping speeds based on process load:

The expression below gives "$\mathbf{S_{avg}}$" average pumping speed which must be maintained to be able to maintain process vacuum pressures at "P" Torr evacuating the vapor/gas load.

In case the process loads are known, pump selection can be easily made by expression,

$$S_{avg} = \frac{62.511 \times T}{P} \left\{ \frac{M1}{Q1} \; \frac{M2}{Q2} \; \ldots \frac{Mn}{Qn} \right\}$$

Where S_{avg} = Pump speed m^3/hr
T = Gas/Vapor abs. Temp, in ºK
P = Process absolute Pressure in Torr
Q_1, Q_2, Q_3 = Gas / Vapor flow rate, in Kg/hr.
M_1, M_2, M_3 = Molar mass, in Kg/mol. of gas /vapor.

For example, a pump is to be selected to handle 10Kg/hr of air load and 5 kg/hr of water vapor load at 50^{O}C and the process vacuum is to be maintained at 20 Torr. The pump capacity comes to 628 m^3/hr i.e. pump selected must have pumping capacity of 628 m^3/hr at inlet pressure of 20 Torr and not a pump having rated displacement of 628 m^3/hr (FAD).

For an installed system air leakage load can be estimated by **"Drop Test / Pressure rise test"** method. Based on the fact that air leaks into the system at a constant rate as long as the pressures in the system is below 400 Torr because of critical flow conditions, the above test is effectively used to determine the leak rate of assembled system.

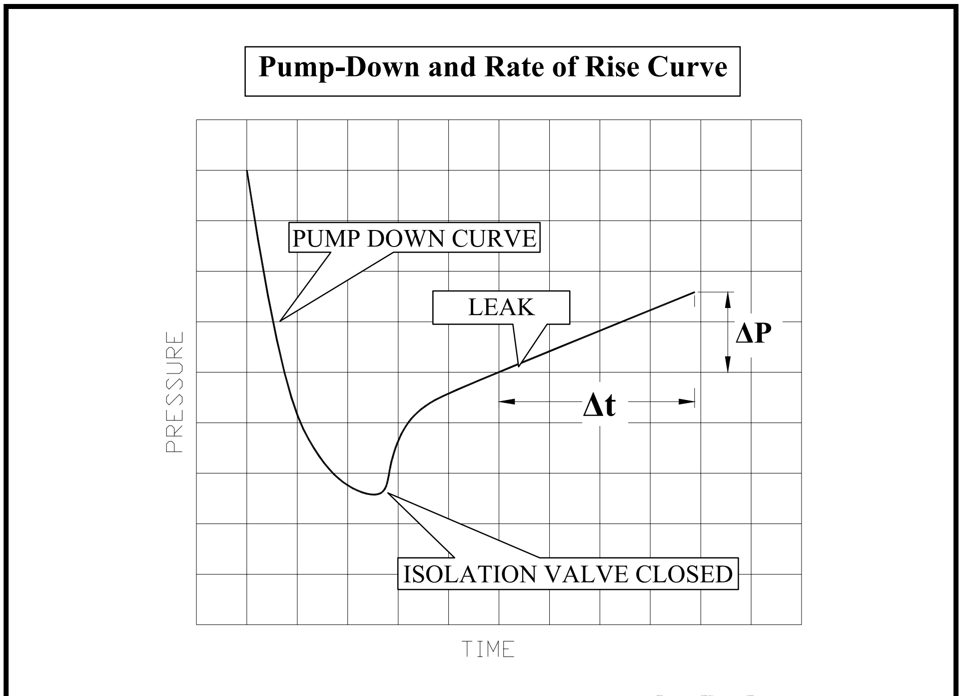
The system is evacuated to pressures between 10-100 Torr and isolated. The pressure is allowed to rise, but not exceeding about 300 Torr and the time lapsed is noted.

The **Leak Rate** "Q_L" is calculated as,

$$Q_L = \frac{\Delta P \times V_s}{t}$$

where Q_L leak tare in Torr Ltrs/sec
ΔP pressure rise in Torr
V_S system volume in Litres
t is elapsed time in seconds

The curve below shows the pump down time and pressure rise. The system is connected to a vacuum pump and evacuated to low pressures. The system is then isolated and pressure allowed to rise. The initial rise may be fast, due to Out-gassing or Virtual leaks and thereafter would get linear. The slope of the curve indicates the Leak rate.



For the known leak rate, the capacity of vacuum pumping system can be evaluated by the expression,

$$S_{avg} = \frac{3.6 \times Q_L}{P}$$

Where S_{avg} = Average pump speed in m^3/hr
Q_L = Leak rate Torr ltr/sec
P = System Pressure in Torr
(For Air, $20^{O}C$, Molecular Wt. 28.9)

For example, in a system of volume $10m^3$ Drop test is done. The system is evacuated to 60 Torr (700 mmHg) and isolated. After 10 minutes the pressure rises to 100 Torr (660mmHg). Find the Leak rate & the capacity of pump required to pump it out maintaining system pressure to 50 Torr.

$$Q_L = \frac{(100-60) \times (10 \times 1000)}{(10 \times 60)}$$

= 666.6 Torr lt/sec ………leak rate

$$S_{avg} = \frac{3.6 \times 666.6}{50}$$

= 48 m^3/hr ………………Pump capacity at 50 Torr

Pipe Sizing

The piping that connects the vacuum vessel to the vacuum pumping system plays a vital role in the overall performance of the system. Sizing of the pipe requires relatively complex calculations based on various factors like Flow conditions – Turbulent, Steady state, Molecular, friction co-efficient, Reynolds's No etc. Too small a pipe would have low conductance (High Resistance) restricting the flow rates due to higher pressure drops across it and too large a piping would increase the capital cost.

As a thumb rule for pressures in the range of 10-100 Torr pipeline "D" may be selected as

$$D = 2.4 (Q)^{0.5}$$

where D= diameter of pipe in mm
Q= Pumping speed in M^3/hr

For a flow rate of 900 m^3/hr the suitable pipe calculated is 72 mm, as per above and 80 NB line, the nearest standard size should be selected.

Vacuum Pump Choice

In order to ensure satisfactory operation of any Vacuum process it is essential that suitable pumping system be used. There is generally no single pump that meets all the requirements of the process and so combination of pumps are increasingly being used to optimize the process performance. Process condensable & non-condensable loads, air leakage loads, out-gassing loads and the working process pressures are the important parameters that influence the pump selection. Some of the widely used pumps for vacuum process are described below along with their limitations.

Ring Type Pumps (e.g. Water Ring Pump, Liquid Ring Pump)

These pumps use water or low vapor pressure fluid as the pumping medium. For this reason in water ring type pumps, the ultimate vacuum gets limited to the vapor pressure of the pump fluid at the working temperature. Owing to the above, Water Ring Pump would stall at around 60 Torr abs. (700 mm Hg) and their working range should be between 60 – 150 Torr (700-610 mmHg). They have further disadvantage of being highly energy inefficient, because most of the power is lost in friction losses of moving the pump fluid inside the pump. This restricts the water ring pump to relatively modest volumetric pumping capacities. Another disadvantage of ring pumps is that the working fluid often has to be treated before it can be discharged or reused as it contains the carry over of condensed product.

Steam ejectors – Single & Multistage

Steam ejectors have relatively high volumetric speeds. However, they require the maintenance of a complete high pressure steam generation facility confirming to IBAR regulations and inspection. They are generally not available as stand alone installations but are found where high pressure process steam is readily available.

Multistage steam ejectors demand inter-stage condensing, putting considerable load on the cooling towers. Apart from the direct steam generation cost, large energy and maintenance cost of secondary equipment such as circulation pumps, cooling tower, softening plant, DM plant and boiler maintenance add to recurring expense.

Rotary Vane and piston pumps

These type of pumps have high power to capacity ratios and are therefore, not available in large volumetric capacities. They are effective for pumping non-condensable loads but have limitations of not being able to pump large & regular quantities of water vapor (condensable loads) released in low-pressure vacuum processes. Various precautions have to be taken if they are used for food grade applications to avoid contamination of process material by the pump oil or back streaming of oil vapors.

Everest Mechanical Vacuum Booster

Everest Vacuum Booster is a Dry pump that meets most of the ideal pump requirements. They work on positive displacement principle. As its name suggests, they are used to boost the performance of water ring / water ejectors/ oil ring/ rotating vane / piston and in some cases steam ejector pumps. It is used in combination with any one of the conventional pumps, to overcome their limitations. Vacuum Booster pump offer very desirable characteristics, making them the most cost effective & power efficient alternative. The pumping speed required to pump out non-condensable air load is given by the expression,

$$S = \frac{2.163 \times T \times M_L}{P}$$

Where S = Pumping speed m^3/hr

T = temperature in ^{O}K

M_L = air load in kg/hr

P = system pressure in Torr

As evident from above, at low pressures, higher pumping speeds are required to maintain the through-put (mass flow rate). Vacuum boosters enhance the pumping speeds by about 3-10 times by virtue of which one can expect higher process vacuum and throughputs even at low pressures where conventional pumps tend to stall.

Everest Mechanical Vacuum booster pumps offer very desirable characteristics, which make them the most cost effective and power efficient option.

The major advantages of Booster combination are,

- **Can be integrated with any installed vacuum system such as Steam Ejectors, Water Ring Pumps, Oil Sealed Pumps, Water Ejectors, etc.**

- **The vacuum booster is a Dry Pump, as it does not use any pumping fluid. It pumps vapor or gases with equal ease. Small amounts of condensed fluid can also be pumped.**

- **Vacuum boosters are power efficient. Very often a combination of Vacuum Booster and suitable backup pump results in reduced power consumption per unit of pumping speed.**

- **They provide high pumping speeds even at low pressures.**

- **Boosters increase the working vacuum of the process, in most cases very essential for process performance and efficiency. Vacuum Booster can be used over a wide working pressure range, from 100 Torr down to 0.001 Torr (mm of mercury), with suitable arrangement of backup pumps.**

- **It has very low pump friction losses, hence requires relatively low power for high volumetric speeds. Typically, their speeds, at low vacuums are 20-30 times higher than corresponding vane pumps / ring pumps of equivalent power.**

- **Use of electronic control devices such as Variable Frequency Control Drive allow to modify vacuum boosters operating characteristics to conform to the operational requirements of the prime vacuum pumps. Hence they can be easily integrated into all existing pumping set up to boost their performance.**

- **Vacuum boosters don't have any valves, rings, stuffing box etc., therefore, do not demand regular maintenance.**

- **Due to vapor compression action by the booster, the pressure at the discharge of booster is maintained high, resulting in advantages such as low back streaming of prime pump fluid, effective condensation even at higher condenser temperatures and improvement of the backup pump efficiency.**

Vacuum Booster being a very versatile vacuum machine is used in a wide range of processes, some of them being;

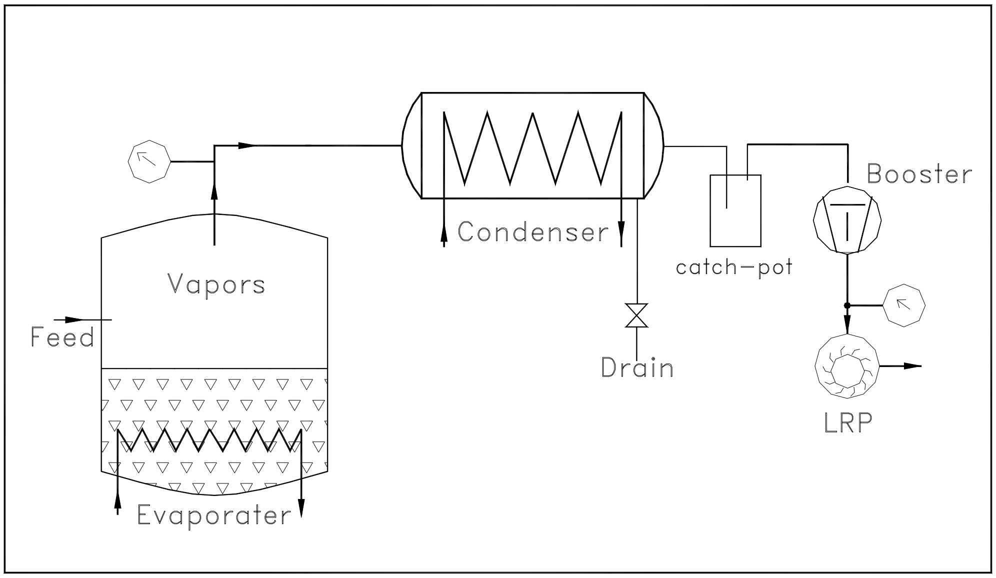
Coarse vacuum applications

- **Vacuum Drying Application.**
- **Tray dryer**
- **Rotary vacuum dryers**
- **Flash Drying**
- **Vacuum Distillation processes.**
- **Solvent recovery.**
- **Vacuum Filtration**
- **Vanaspathi Oil De-odourisation.**
- **Replacement of Steam Ejectors.**
- **Enhancing the performance of Water Ring Pumps /Water ejectors**
- **Vacuum Flash cooling / Evaporative Cooling**
- **Vacuum Crystallization**

Medium Vacuum applications

- **Efficient backup for Diffusion Pump Systems.**
- **Thin Film Deposition /Coating**
- **Short path/ Molecular distillation.**
- **Solvent Recovery.**
- **CFL ,Tube Light and General Lighting industry.**
- **Object & Roll Metallisers.**
- **Vacuum Heat Treatment and Degassing / Vacuum Furnaces**
- **Semi – Conductor Processing.**
- **Transformer oil De-humidification**
- **Chemical laser applications**
- **Freeze Drying**
- **Vacuum Impregnation**
- **De-humidification**
- **De-gassing**

TYPICAL BOOSTER INSTALLATION



The figure above shows a typical Booster- Water ring combination, generally used for attaining lower process pressures and high pumping speed for getting high process efficiencies in terms of higher yield, lower process time and higher purity & recovery. Various other combinations and installation layouts are possible to meet the specific demand of the process.

The above article has been focused on the applications and use of booster in chemical industry- Coarse vacuum applications. For other applications of medium vacuum of the range 1 Torr - 0.001 Torr refer:

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