**Understanding Process Vacuum for Process Improvement**

Through this article we wish to give practical tips to boost process capacity, increase product quality and reduce cycle time in batch or continuous systems, performed under vacuum. Attempt is made to broadly discuss the basic process fundamentals, conventional vacuum pumps used in the industry and case studies having achieved process improvements.

Distillation systems are widely used in chemical and pharmaceutical industries where the operation goes by several names such as Vacuum Distillation, Solvent Recovery, Vacuum Drying, Tray Drying, Flash drying, Thin-film distillation, High vacuum distillation, Molecular distillation etc. A typical distillation process is discussed below:

**Typical Vacuum Distillation System consists** of an evaporator, Vapor-liquid separator, condenser and a vacuum pumping system. In the evaporator, the product is heated to elevated temperatures to generate vapors, which are passed through Vapor-Liquid separator (VSL); the condenser and finally the non-condensable are ejected out through the vacuum pumping system. Condensers are maintained at relatively lower temperatures so that the evaporated vapors can condense, causing drop in pressure. It is this differential pressure, which pushes the vapors from the evaporator to the condenser. The vacuum pumping system maintains the process vacuum by continuously pumping out leakages and other non-condensable loads, generated during the process. Most of the chemical processes are carried under vacuum for maintaining low process temperature and inert working conditions.
“How can process capacity be increased?” The answer to this can easily be worked out by analyzing the following: -

- **By how much do we need / can increase the output?**
- **What is system design capacity?**
- **Are current process yields optimized?**
- **Additional constraints needed to be impose (i.e., capital, time or regulatory)?**
- **Where is the bottleneck?**

The answers to these basic questions can dramatically improve the process efficiency. In most of the processes the basic answer to the above would be to “**Improve the Vacuum pumping system capabilities**”. We discuss under, basic terminology used frequently in reference to the vacuum process.

**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 absolute pressure, in Torr (mmHg),

<table>
<thead>
<tr>
<th>Vacuum Level</th>
<th>Pressure Range</th>
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<tbody>
<tr>
<td>Coarse Vacuum</td>
<td>10 – 760 Torr</td>
</tr>
<tr>
<td>Medium Vacuum</td>
<td>0.001 – 10 Torr</td>
</tr>
<tr>
<td>Fine Vacuum</td>
<td>10⁻³ – 10⁻⁷ Torr</td>
</tr>
<tr>
<td>Ultra High Vacuum</td>
<td>&lt;10⁻⁷ Torr</td>
</tr>
</tbody>
</table>

The performance of a vacuum process largely depends on the right vacuum pumping system. Many companies have been able to improve process efficiency and reduce process time considerably by making modifications in the vacuum pumping systems only. We shall discuss a few case studies highlighting the fact that proper selection of vacuum system can enhance the process performance, reduce process time, achieve higher product purity and reduce power consumption. It is, however, important to understand the terms **Capacity, Throughput and Ultimate/ Blank-off vacuum** of a vacuum pumping system/pump as they play very vital role in the overall performance of the vacuum system. Too small a pumping system would result in inefficient or no process whereas too large a pumping system would result in high capital and operating cost.

**Capacity** is generally referred to as the volumetric displacement of the pump at either free air Delivery (FAD) conditions or at the inlet conditions. It is also referred as the pumping speed of pump. It is generally calculated based on the geometrical displacement of the pump with conventional units as Lts/min, m³/hr.

**Throughput** is the product of capacity and Pressure (abs) with conventional units Torr–Lts/min. Therefore, for a pump of constant displacement, the throughput would drop with the drop in the inlet pressure.
Ultimate vacuum/Blank-Off vacuum: - The limiting pressure approached in the vacuum system after sufficient pumping time to establish that further reductions in pressure will be negligible. It is the final pressure achieved by a pump under blank-off condition when the throughput is practically zero. At this stage the pump does not pump any air/vapor and no further drop in pressure is possible.

For most of the chemical processes vacuum-pumping system is designed to take care of process load and maintain the process to the desired levels of pressures. Process loads mainly consist of:

- Plant air leakage load.
- Process non-condensable such as dissolved gases.
- Process condensable load - vapors which escape the condenser

The sum of the individual loads must be effectively pumped out to maintain the process vacuum. For example a load of 10Kg of Air Leakage at 100 Torr (660mmhg) vacuum, 20°C needs a pump of pumping capacity 63 m³/hr and for the same load at 10 Torr the Pumping speed required would be 630 m³/hr and at 1 Torr would need a pumping speed of 6300 m³/hr.

Mechanical Vacuum Boosters, manufactured by EVEREST, are being extensively used in chemical process industry to boost the performance of the vacuum pumps, especially in low-pressure range, where conventional vacuum pumps have poor volumetric efficiency. Everest Boosters are capable of moving large quantity of gas at low pressures, with far smaller power consumption than for any other equipment now available.

The internals of a Booster are totally free of any sealant fluid, and therefore the pumping is dry. Due to the vapor Compression by the booster, the pressure at the discharge of the booster is relatively high, resulting in higher volumetric of the backing pump. Everest Twin Lobe Boosters are used in series with a variety of backing pumps to achieve higher speeds and lower ultimate pressures.
The Table below gives a rough estimate of how the boosters enhance the working vacuums of the process when installed in combination with various types of vacuum pumps. Various types of backing pump can be used, depending upon the system requirement and ultimate vacuum needs. However, the final vacuum is governed by the suitable selection of the backing pump and booster combination. The table below gives a broad range of vacuum achieved with various backing pumps combinations.

<table>
<thead>
<tr>
<th>Vacuum Pump</th>
<th>Absolute Pressure Range</th>
<th>Pressure achievable with Booster</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Stage Ejector</td>
<td>150 Torr</td>
<td>15 – 30 Torr</td>
</tr>
<tr>
<td>Water Ejector</td>
<td>100 Torr</td>
<td>10 – 20 Torr</td>
</tr>
<tr>
<td>Water Ring Pump</td>
<td>40 – 60 Torr</td>
<td>5 – 10 Torr</td>
</tr>
<tr>
<td>Liquid Ring Pump</td>
<td>20 – 30 Torr</td>
<td>2 – 5 Torr</td>
</tr>
<tr>
<td>Piston Pumps</td>
<td>20 – 30 Torr</td>
<td>2 – 5 Torr</td>
</tr>
<tr>
<td>Rotary Piston Pumps</td>
<td>0.1 Torr</td>
<td>0.01 Torr</td>
</tr>
<tr>
<td>Rotary Vane Oil Pump</td>
<td>0.01 – 0.001 Torr</td>
<td>0.001 – 0.0001 Torr.</td>
</tr>
</tbody>
</table>

**Water Ring Pump** :- is the most widely used vacuum pump in the chemical process industry and therefore, is broadly discussed for understanding and improvement.

**OPERATING PRINCIPLE OF A WATER RING PUMP**

*In a cylindrical housing, partially filled with sealing liquid, a multi-blade impeller on a shaft is positioned eccentrically. Port plates with inlet and discharge openings are positioned on either side of the impeller. A liquid ring is created by the centrifugal force generated by the rotating impeller. The centrifugal force holds the liquid ring against the inner wall of the pumping chamber. Since the impeller is located eccentric to the pumping chamber, the depth of entry of the blades into the liquid ring decreases and increases as the impeller rotates. This creates increasing impeller cell volume on the inlet port side, creating a vacuum. On the discharge port side, the impeller cell volume decreases, as the blades move further into the liquid ring, increasing the pressures, until discharge takes place through the discharge port. A continuous flow of fresh sealing liquid is supplied to the pump via the sealing liquid inlet.*
The figure above shows typical pumping speeds of Water ring pump and Ejector, which are very popular in the chemical process industry. These pumps have water as the sealing/motive fluid and therefore, cannot work beyond the saturated vapor pressure of water, to corresponding temperature. As evident from the curve above, the effective pumping speed drops drastically at low-pressure range and the overall process becomes inefficient, un-economic and slow. Liquid Ring Pumps are used throughout process industry. Unfortunately, they suffer from few limitations, such as:

- The final vacuum achievable is largely dependent on the vapor pressure of the pump fluid corresponding to the working temperatures. For water sealed pumps, the lowest practical operating pressure for two-stage design would be 60 Torr (700mm Hg) for exit water temperature at 30-32 ºC.
- Their energy consumption per unit of gas pumped is higher since most of it is lost in handling pump fluid.
- It requires large quantities of sealing fluid.
- It adds load on the ETP system.

Economical solution to overcome the above limitations is installation of mechanical vacuum Booster to boost the vacuum pumping system performance. Case studies discussed establish that drastic process improvements have been achieved on installation of Mechanical Booster only. Mechanical vacuum boosters cover a vast capacity & pressure range making them an ideal choice for process engineers for practically all process applications.
Invariably the process demands higher working vacuums and the process engineers’ end up selecting higher capacity pumps 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°C, ideal pump should have a capacity of 130m³/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.**

**BOOSTER DISTILLATION UNIT**

**EVEREST MECHANICAL VACUUM BOOSTER**
Case Study 1

A Vanaspathi oil De-odorizing plant in Bikaner, Rajasthan was carrying out the process of de-
odourisation of oil in a batch process of 10MT batch. The oil was heated to about 270°C in the
evaporator and the vapors generated were passed through Barometric leg direct water
condenser followed by Water-ring pump of 7.5HP. The process was maintained under
vacuum of the range 680-700 mmHg, the best a good water ring pump could achieve. During
the process about 100Kg/hr of stripping steam was injected into the oil. The entire process
had about 10-12 hours of cycle time. The process engineers wanted better process
vacuum for better product quality. The conventional option of installation of multi stage
Steam-jet ejectors was ruled out due to unavailability of additional high-pressure steam.

The technical team of Everest studied the process and available utilities and suggested
installation of Mechanical Vacuum Booster. To increase the process vacuum the vacuum
pumping system capabilities had to be improved so that lower pressures could be achieved at
the evaporator. There was no need to reduce the pressures at the condenser, as higher
pressure in the condenser would increase the condenser efficiency. A mechanical vacuum
 Booster combination was proposed for installation between the evaporator and the condenser
so as to create low pressure at the evaporator.

The mechanical Vacuum Booster combination was installed, as illustrated in the figure. The
installation was easily and quickly completed, as it required little modification in piping only
and was done without disturbing any of the process vessels.

System was put in operation and following results were observed:

- Required vacuum levels in the range of 755-758 mmHg (3-5 Torr) were
  achieved and the desired product quality was easily achieved.
- Due to the vapor compression at the discharge, condenser efficiency
  increased allowing less stringent control on inlet water temperature.
- Requirement of stripping stream was reduced to almost half. The
  specific volume of steam at 60 Torr is about 23m³/kg and at 3 Torr is
  about 407m³/Kg, almost 17 times higher. The reduced quantity of
  stripping steam was net direct saving apart from the indirect benefit of
  reduced load on the condenser and the cooling towers.
- A Pre-condenser installed in between the Evaporator and the Booster, to
  cool the incoming hot vapors, acted as a trap and a fairly good amount
  of evaporated FFA vapors condensed in there. This condensed FFA was
  drained after every batch. The contamination of the water in the
  condenser was therefore, minimized reducing load on the ETP system.
- The process cycle time was reduced by 2 hours.
Technical comments: The vapors from the evaporator travel towards the condenser due to the differential pressures that exist between the two, created by the temperature difference. The rate of flow of vapors from the evaporator to condenser would, therefore, depend on the differential pressure and the line conductance connecting the two. In this configuration the mechanical Vacuum Booster pumps out the vapors generated in the evaporator and force them towards the condenser. Due to the mechanical pumping action by the Boosters low pressures are generated in the evaporator, accelerating the vapor generation whereas higher pressures are created in the condenser, accelerating vapor condensation.
Case Study2

A Pesticide manufacturing company in Lote Parshuram, Maharashtra had a process involving solvent recovery of Ethylene dichloride (EDC). The process was being done under vacuum and the vacuum pump used was conventional water ring type of 330 m³/hr. The process pressure levels were in the range of 80-90 Torr and the batch cycle time, to attain product purity of 95%, was 8-9 hours. The process engineers wanted better product purity for which the team of Everest studied the process and recommended improvement in vacuum levels by installation of 800 m³/hr vacuum booster.

As per the Raoult's law, "In a solution, vapour pressure of a component (at a given temperature) is equal to the whole fraction of that component in the solution multiplied by the vapour pressure of that component in the pure state".

Based on the above law, recommendations were made for better vacuum and it was anticipated that with the increase in vacuum, process would be able to achieve higher product purity with reduction in time. Vacuum booster was installed with a mechanical bypass line across it, as shown in the figure (Case 2 Fig 2). The same water ring pump was used as a backing pump to maintain a backing pressure, at the discharge of the booster, to around 80 Torr. The process operation was modified slightly in which initially the booster was by-passed and solvent recovery done directly by Water Ring Pump, as the initial solvent recovery was at a much higher rate. Subsequently, as the concentration of the solvent got reduced, demand for better vacuum was essential and at that stage, the by-pass valve was closed and booster switched on. With booster in operation, the process pressure dropped to 20-25 Torr from 80-90 Torr, thereby, accelerating solvent recovery. The product of purity 97-98% was achieved with reduction in batch cycle time by three hours. This amounted not only in better product purity but also increase in the production by about 30%.
Technical Comments:

In the process of solvent recovery / drying, as per Raoult's law, the initial rate of evaporation of solvent, when the percentage of solvent is more, is high. Gradually, the rate of evaporation drops and can only be increased either by increase in temperature or reduction in pressure. At this stage, booster is put into operation reducing the system pressure which in turn accelerates the rate of evaporation resulting in more evaporation of solvent and reduction in process time.
Case Study 3

An energy drink powder manufacturing company at Nabha, Punjab had a process of multi-pass evaporation for drying of viscous solution of energy drink powder. The drying of the solution was done up to final concentration of 82%, in multi-pass evaporator, which was then transferred to vacuum tray dryers for total drying. The multi-pass evaporation (MPV) had multiple evaporators followed by direct (Barometric leg) condenser and 7.5HP Water Ring Pump. The cooling water in the direct condenser was of 30ºC and the condenser pressure was maintained at about 100 Torr. The total batch cycle time was 2 hours 30 minutes.

The client wanted reduction in batch cycle time with increase in concentration up to 85%. Everest technical team studied the installation and suggested installation of 3HP Mechanical Vacuum Booster between the multi-pass evaporator and the condenser (refer figure). On installation, client was able to achieve the following improvements:

- Reduction in batch cycle time by 20%.
- Increase in Vacuum from 100-120 Torr to 40-45 Torr.
- Increase of concentration to 84% in the reduced time.
- Dependence on cooling water temperature was minimized since the saturated vapour pressure of water in the condenser, after installation of booster was of little importance.
**Technical Comments:**

In a direct condenser, the saturated vapour pressure of the cooling water determines the condenser pressure. In the last pass of evaporator, the vapour temperature is close to 50-55°C at which the saturated vapour pressure is about 56-60 Torr. The differential pressure between the evaporator and the condenser is the net driving force, driving vapours from evaporator to condenser. Mechanical Vacuum Booster installed accelerates the transfer of vapours resulting in higher through-put, higher purity & reduced process time.