Successful utilisation of mechanical vacuum pumps in steel degassing

Mechanical dry vacuum pumps are increasingly replacing traditional steam ejectors in vacuum secondary steelmaking plant applications because of their ‘greener’ credentials and proven record of reduced cost of ownership by as much as 97% compared to steam ejectors. This calculation takes into consideration the cost for production of steam, water circuit pumps, maintenance and disposal of condensate versus lower power consumption of mechanical pumps with its maintenance cost.

To achieve and maintain these economic advantages at high production rate over many years, good systems design and maintenance of equipment are required.

Edwards Ltd, a major manufacturer of vacuum pumps, has the largest installed base of dry pumps in the global steel industry with many years of field experience.

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The steel market is increasingly demanding higher grade steels, be it for mobility such as automobiles, ships and railways, or structural steel for bridges and high buildings.

The use of vacuum treatment of molten steel to ensure removal of nitrogen, hydrogen or carbon, appropriate to steel application requirements, is a key part of the modern steelmaking process route. The various vacuum degassing processes used are proven methods and have been traditionally equipped with steam ejectors to help produce the vacuum.

However, over the last 15 years, use of dry vacuum pumps has increased markedly. Starting from installations in foundry billet operations that were relatively light duty, their utilisation has progressed to the high volume requirements for continuous caster operations seen today. These operations require that the pumping equipment runs continuously during campaigns with high uptimes, and these demands on pumping system design and reliability currently dominate conversations in the industry.

The change from steam ejector to a mechanical pump is not just an exchange of equipment, rather, it is a change in paradigm, requiring a different approach in both operation and system design.

This article outlines the difference between a steam ejector as a mass conveyor and the mechanical vacuum pump as volumetric conveyer, and the implications for systems design (sizing, installation in pump room, filters), on-site performance testing, operation and maintenance for use in VD and VOD facilities, with the target to achieve an optimal solution.

STEEL DEGASSING VACUUM REQUIREMENTS

The main secondary metallurgy treatments under vacuum are Vacuum Degassing (VD), Vacuum Oxygen Decarburisation (VOD) and Ruhrstahl-Heraeus (RH). The process regimes have, in common, a pump down requirement to 0.67mbar (0.5 torr) within 5-9 minutes and a treatment of about 20 minutes at this pressure. VOD and RH-OB variants include a preceding oxygen blow at higher pressures to decarburise the steel.

The suction speed requirements at low pressures are large, with approximately 1,200m³/h/t of steel for VD, 1,500m³/h/t for VOD and 3,200m³/h/t for RH. These are values based on field experience, but may vary depending on stoichiometric metallurgy design calculations. These numbers refer to optimised installations, not considering unnecessary additional gas loads.

The installed capacity of steam ejectors in older installation is typically oversized to counter its creeping deterioration of performance due to dust deposits in the nozzles and extend its maintenance intervals. Thus it is not a suitable benchmark for comparative sizing of mechanical vacuum systems.

The process gases are a mixture of Ar, N₂, H₂, C, CO and others, and with large amounts of fine pyrophoric dust also present.
which adds to the operating cost.

Steam ejectors are mass conveyors, as the operating principle is about moving a defined amount of gas, independent of gas temperature. Performance is measured, for instance as: kg/h DAE (Dry Air Equivalent). The performance within one stage remains quite constant. Figure 2 shows 20-30lb/hr range per stage.

Features and benefits
- No moving parts – low maintenance regime and spares inventory
- Large internal clearances – requires just regular cleaning after clogging and decreasing performance
- Filter beneficial but not mandatory
- Lower initial installed suction capacity limitation due to low additional investment
- No inlet temperature limitations, in case no filter is used

Disadvantages
- Capital cost high when steam not available from BOF as boiler for steam production required
- Even if steam available, in some cases boiler required to improve quality of steam
- High power consumption for steam production with boiler
- Uprating of performance after installation not possible
- Maximum cooling water temperature 25°C to ensure condenser performance
- High disposal cost for condensates, liquid-ring-pump feed water and cleaning slush
- Time consuming maintenance in particular if no filter is used
- Low readiness for cyclic production in campaigns as pre-heating of boiler required

STEAM EJECTOR TECHNOLOGIES

The steam ejector is a simple device consisting of three basic components: a motive steam nozzle, a suction chamber and a mixing diffuser, as illustrated in Figure 1.

The motive steam enters the ejector through the motive fluid nozzle and is expanded into the mixing diffuser, converting pressure energy into velocity energy. The steam entrains the suction gases and the mixture proceeds through the mixing diffuser where some of the velocity energy is converted back into pressure energy, enabling the mixture to be discharged at a higher pressure than the suction pressure.

The achievable compression ratio is highly dependent upon the quantity and quality of motive steam.

Multi-stage steam ejector systems are required to enable lower suction pressures to be achieved than can be produced by a single stage unit. The lowest achievable ultimate pressure of this technology is ~0.5mbar, while mechanical systems can achieve ultimate pressures of 0.001mbar.

Inter-stage condensers are required to keep the steam consumption of the following stage within a practical limit. The operating steam from the upstream stage of the system is condensed leaving only the saturated non-condensable gas to be handled by the next stage.

The condenser performance strongly depends on cooling water temperature, typically 25°C max., whereas the Edwards mechanical vacuum system allows up to 38°C under ambient conditions up to 40°C.

Two degassing installations use a liquid ring pump for the atmospheric stage, which limits the steam consumption, however these consume high power due to the mechanical work of the principle of moving seal water to build a ring. In addition this pump requires maintenance and produces waste water for disposal.

MECHANICAL VACUUM PUMPS

Unlike steam ejectors, mechanical vacuum pumps are volumetric conveyors. As the internal pump volume, which is exposed to the vacuum system, increases, the gas from the vacuum system expands to fill this added volume and the system pressure drops. It is this phenomenon which makes mechanical vacuum pumps work.

For compression to atmospheric pressure the screw pump principle is, today, state-of-the-art in steel degassing. Two shaft screw-shaped rotors push the process gas by multiple windings out to the exhaust (see Figure 3).

Traditional single ended screw mechanisms which are compressing towards one end may suffer additional axial load and heat generation at the exhaust. To overcome this, Edwards technology either has a high technology single screw with tapered pitch design or double ended screw
mechanism as shown in Figure 4, which compresses the flow to both ends. This ensures longer lifetime of bearings and avoids overheating and consequential seizures in the harsh duty of steel degassing.

Screw-type vacuum pumps have excellent ultimate pressures compared to steam ejectors of <<0.1 mbar at inlet (depending from individual design) compressing to atmospheric pressure in the outlet.

Multiple layers of Roots vacuum pumps or so-called mechanical boosters (MB) are added to achieve high performance towards lower pressures, with very low power consumption!

A schematic of a Roots pump is shown in Figure 5. These pumps are designed either as two-shaft rotor machines which convey the gas in one step without inner compression or as pre-inlet gas cooled pumps which are used in some designs with higher pressure stages.

All pumps are equipped with frequency inverters for soft start of the screw pumps and the boosters during pump down.

VACUUM PHYSICS – BOYLE’S LAW

In the mid 17th Century, Robert Boyle observed that the product of the pressure and volume of a confined gas held at a constant temperature are observed to be nearly constant. The product of pressure and volume is constant for an ideal gas as per the well-known equation,

\[ p \cdot V = \text{constant} \]

The volume captured at low vacuum contains low number of molecules, with compression from stage to stage the mass density in the gas increases. This is illustrated in Figure 6.

During pump-down, the boosters are filled with process gas of higher mass density as the pressure is high, consequentially the compression work is far larger and power consumption would, theoretically, go up to impracticable values with regards to power requirements. This is why all mechanical boosters start with lower frequencies, by means of capturing smaller volumes at higher pressures and is why the suction speed curve of a mechanical system increases towards lower pressures to a maximum, while mass flow performance decreases (see Figure 7).

The control philosophy varies depending on vacuum systems concepts and booster compression capability of different manufacturers.

The Edwards modular concept considers starting of boosters at atmospheric pressure then as the pressure decreases, the boosters begin to steadily accelerate towards full speed against their current limits set on the frequency inverter. This allows us to push the pumps within safe limits and achieves an optimised performance right from start of the system, as shown in Figure 7.
System performance increases from installed 1,000m/hr backing pump towards lower pressures.

By design principle the power consumption of boosters is lower compared to atmospheric pumps, as process gas is conveyed only into the next stage and thus the compression work is lower. The installed motor power on a booster depends on two factors, the delta pressure capability, with intention to use it, and the mechanical loss due to high inertia of big masses:

- Boosters with high delta pressure capability are helpful to enable short pump down times, in particular when installed next to the screw pump
- Large boosters with low rotational speed consume additional power to overcome the inertia of the heavy rotors, and at the same time the acceleration is slower, impacting the pump-down time performance

The Edwards system design concept utilises strong compression in the second stage and in the top stage a new design high performance booster with innovative lightweight rotor technology as shown in Figure 8, which is suitable to cope with dust.

**PERFORMANCE TESTING**

Performance measurement on mechanical vacuum pumps and systems is described in DIN28426. The use of a pressure dome (see Figure 9) ensures stable gas flow conditions into the pump inlet. A volumetric flow meter is connected to the gas inlet port, and a pressure gauge at a clearly defined port on the pressure dome to ensure that the results are not influenced by turbulence. All instruments must be calibrated on a regular basis, and selected in the appropriate range for the individual pump or system to ensure reproducible results.

In-house testing of Edwards’ mechanical systems is executed before shipment following this method to ensure the full performance.

For on-site measurements during commissioning the simple method of measuring mass flow with HEI-calibrated nozzles (see Figures 10 and 11) is standard practice. HEI nozzles have been developed by the Heat Exchange Institute based on wider calibration works, and are commonly accepted as flow metering standards. The nozzles are applied to ports on a test rig, which is connected to a branch of the suction pipe downstream of the filter. The pressure gauge is typically installed on a port provided at the inlet manifold for this purpose.

As gas and conditions are not ideal (even in a laboratory), the volumetric flow rate, evaluated at different vacuum pressures, can be calculated from the following equation:
The system should be leak tested to avoid the effects of additional gas load. A tolerance of 10% according to DIN 28426 and ISO 1607 on suction speed measurement is permissible to compensate the normal inaccuracies.

**ADDITIONAL GAS LOAD**

System leak tightness is essential for the efficiency of vacuum systems. A hole with diameter of 1 cm, for example, causes a leak of 65 kg/hr. This corresponds to a suction speed requirement of 81,800 m/hr at 0.67 mbar, an equivalent to a process gas performance requirement of a 55 t VD system! As an increasing leakage rate will lead to a rise in achievable process pressure, this could affect attainment of the appropriate steel degassing required and, in the worst case, affect steel quality.

It is recommended to introduce regular leak test routines for filter and tank by implementing an automatic pressure rise test. Localisation of leaks can be done with leak detectors as shown in Figure 12.

Leaks on gas system connections (welded or flanges), as well as protection gas for cameras, water vapour from the water-cooled tank seal, or humidity from the refractory can all add unnecessary gas load to a system.

These gas loads add to the process gas flow and so require additional performance to achieve the required process pressure. In particular, existing refining stations require careful investigation and overhaul to minimise this gas load. Water seals should be rebuilt to dry solutions, cameras consuming high amounts of protection gas should be replaced, as well as any others sources of additional gas load, and all leaks found then sealed.

This will lead to an optimised system as investment for equipment and consequential cost, such as integration into control, footprint for pump room and foundations.
will be lower, and return on investment will be faster, as fewer equipment requires less maintenance and has lower media consumption, thus lower cost of ownership.

Last, but not least, new refractories must be completely dry before starting production as water evaporation will limit achievable pressure and add load on the pumps, which can lead to overheating.

**COOLING WATER QUALITY**

Good quality cooling water is important for a mechanical vacuum system, as passages for cooling water on the pumps are relatively small, compared to other equipment in a steel plant.

Cooling is required for:
- Direct cooling of boosters for oil, mechanical seals and process gas flow
- Direct or indirect cooling of screw pump

The cooling water is assumed to come from a water treatment plant.

However the passages of cooling water circuit on the Edwards mechanical pumps can be easily flushed for cleaning, as circuits are not branched and passages are sufficiently wide.

It is good practice to install two water filter cartridges in parallel in the main cooling water line to the vacuum system to ensure particles are retained from the cooling circuit of the individual pumps. Three-way valves allow switching from one filter to the other in case of clogging. Pressure gauges at inlet and outlet indicate the pressure drop across the filter and hence the status of clogging and requirement for cleaning.

The cooling water temperature should be 38°C max., the differential pressure across the system 2 bar with a maximum of 5 bar(g) at the inlet.

**INSTALLATION OF THE MECHANICAL VACUUM SYSTEM**

For several reasons it is good practice to install mechanical vacuum pump systems in a protected environment. One aspect is ambient temperatures, which are for mechanical vacuum pumps typically in the permissible range of 5-35°C.

Depending on region, air conditioning may be required to ensure appropriate cooling in hot summers, while in cold winters, heaters will prevent cooling water from freezing when the system is not in use or ensure oil is not too cold when pumps are started. Also, the vacuum system would be protected from steel plant dust.

Another aspect for modern steel plants is to protect operation personnel from noise, as vacuum pumps are rotating machines and create noise.

Noise into the stack can be lowered with silencers on the
between motor and pump can easily be checked and exchanged if worn.

Installation drawing of the systems give advice on good foundation design. The inlet manifold should be welded to the support as opening or closing of the inlet valves can move the bellows quite forcefully.

Good accessibility of each pump will ensure easy inspection and maintenance routines. This can be ensured by design of ducts for cables and all supply media such as cooling water, nitrogen, compressed air.

A crane should have free access for exchange of pumps or motors and to keep intervention time to a minimum.

The lowest points in the pump system as well as exhaust manifold should offer ports to drain condensate on a regular basis, as the process gas contains water vapour, in particular in humid regions.

A local control box installed close to the vacuum pump system will ease up any testing of pump system without a second person in the pulpit, eg, for maintenance purposes such as leak testing, functionality testing, or cleaning procedures.

A typical pump room is shown in Figure 13.

MAINTENANCE

On Edwards vacuum systems, most of the maintenance work can be owned and executed by site personnel. All mechanical pumps should be regularly inspected for undue noise and vibrations to prevent from unexpected failures.

Oil levels of the gear boxes can easily be checked on the sight glasses and oil topped up if needed. Drainage points at the lowest points allow release of possible condensate in the system; this is good practice before starting a system from cold.

The interior of the pumps can easily be checked for dust deposits, but with normal occurrence of dust, only the screw pump will require cleaning from time to time, as it is the lowest point of any mechanical system. The intervals depend on usage rate, quality of filter bags but also on presence of humidity, which can make the dust very sticky.

The Edwards IDX screw pump design allows an easy in-situ solvent flush cleaning, no less than once per year.

As dust ingress would lead to contamination of oil in the gear box and hence require more frequent oil changes, a purge gas flow of nitrogen is used to protect the gear box from process gas.

Other maintenance works are checking and cleaning of strainers, oil filters and media supply (nitrogen, cooling water) pipes and ports, intervals are depending from usage rate and quality of filter bags (see next section). Couplings...
Interlocks, warnings and alarms must be properly integrated into the control system. Functionality of safety relevant instruments should be highlighted on the HMI to ensure early exchange. HMI design should be well thought out to allow the operator a good overview. Only relevant information should be shown on the desktop for operation. Detailed information can be displayed on other layers and looked at on demand. This will enable quick decisions for the operator. Data storage of historical trends is helpful for any tracking of issues.

Typical process cycling will work in pre-programmed sequences, which the operator can easily utilise with push-buttons or on a touch screen for ‘start’ and ‘stop’ of the vacuum system and process. A lamp should be associated with each button to indicate which sequence is in progress. This will make the operation simple and avoid failures.

The tank system may also provide a nitrogen gas admittance facility to allow the operator to manually increase tank pressure if required due to slag-foaming. All sequences should have safety relevant interlocks included, as well as best-practice operation methods for long life time of pumps.

The Edwards scope includes a detailed document, describing options for sequences, interlocks, alarms and warnings. The control of the vacuum system is then part of the automation for the refining station and can be easily adjusted to the individual process requirements without support of the vacuum pump system supplier.

**SUMMARY**

Good cooperation between steel plant, engineering and vacuum system supplier can create an installation with utmost environmental and economic success.

A well-designed refining station with optimised volumes and leak rates, a good filter system, an appropriate installation of vacuum pumps and a simple and safe automation, are key to success.

Last, but not least, trained site personnel will make the success durable, with proper usage and maintenance of the equipment. **MS**

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