Recent Operating Experience with Dry Running Vacuum Pumps on Vacuum Degassing and Vacuum Oxygen Decarburising Systems

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INTRODUCTION

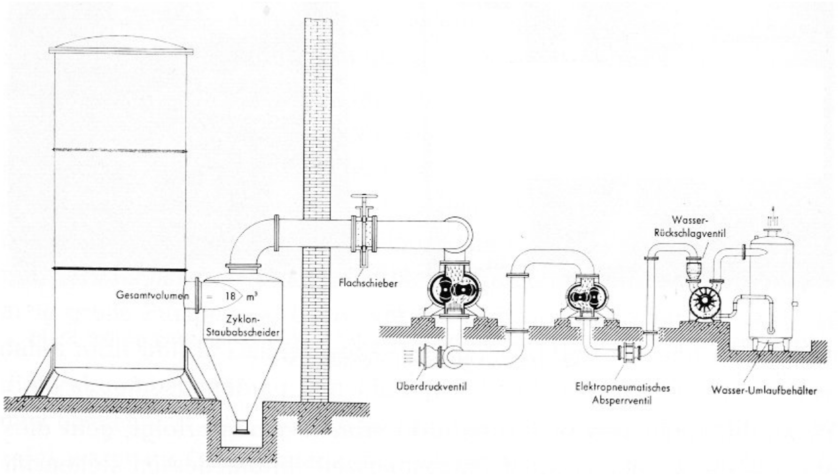
Investment in steel vacuum degassing processes, both in new plant and upgrades of existing plant, is continuing as steel companies see the opportunity to increase the value added component of their products by improving quality and supplying more speciality grade steels. In the area of ladle refining recent advances in degassing processes utilizing dry mechanical vacuum systems, in place of fluid-sealed water ring and/or steam ejector systems, offer clear savings in running costs, maintenance costs, and installation space, and also offer increased speed, flexibility, and overall productivity to steel degassing operations.

Vacuum degassing (VD) and vacuum oxygen decarburizing (VOD) are the main processes in secondary steel making. The large volumes of dissolved metallurgical gases arising from these processes, and the generation of large amounts of metallic fines and oxide dust, require high-capacity vacuum pumping equipment which is also very robust. Large Roots style mechanical vacuum booster pumps, designed for high dust tolerance, are the major component of such "dry" vacuum degassing systems, and when backed by rugged, dry, mechanical vacuum pumps form today's advanced dry pump systems. These systems are superior to previously-used steam ejector systems particularly in that they enable better dust handling, increased pumping speed in the crucial processing pressure zones, and significantly reduced environmental impact.

Background

Dry running mechanical vacuum pumps are not new and have been used in the metallurgical industry for degassing since the 1920s. The first Roots type mechanical vacuum boosters were installed by Wilhelm Rohn in 1920 at the W. C. Heraeus GmbH works in Germany. Here they had a vacuum induction furnace and poured up to 4 tonnes of non-ferrous metal at pressures of 2.7mbar / 2torr to 6.7mbar / 5torr, and 1600^{o}C to 1700^{o}C. In fact this was not truly dry system since the mechanical boosters were backed by water sealed liquid ring pumps (LRPs) (Figure 1).

Figure 1



However, as early mechanical vacuum pumps were not designed to handle large quantities of gas, it was not until the early 1950s, following a patent in 1943 by B.E.L. DeMare, that Bochumer Vereins in Germany developed degassing processes for tonnage quantities of steel which are now common today. Steam ejector systems then superseded mechanical pumps because they were capable of handling the very large gas loads involved, and their capital and maintenance costs were lower at that time. As energy costs became more significant, the later use of LRPs in place of the final stage "hogging" steam ejector (usually an extremely large ejector to achieve an initial, fast removal of air from the system) grew in popularity. The situation has now come full circle. With reduced costs now available in manufacturing large capacity precision mechanical boosters, and with the invention of the suitably large dry running backing pumps (and in particular the dry claw mechanism), the potential for a completely dry vacuum pumping systems with sufficient capacity for modern steel degassing facilities has been realised.

Pumping performance requirements

The basic performance parameters and requirements in a typical steel degassing pump system have been categorised [1] and are listed in Table 1. It is of course essential that the specification for the vacuum pumping system is both accurate and realistic - it should be carefully noted that specifications of legacy steam ejector systems in particular may contain excessive margins to allow for ejector degradation due to contamination and for large system air leaks. Significant air leaks must be properly addressed via suitable maintenance otherwise unwarranted extra pumping capacity will have to be installed. Note also that fast, empty pump down time specifications may incur additional installed costs to no advantage if actual degassing operations only ever require a controlled decrease in pressure.

To meet the high speeds required, the systems should use an adequate numbers of large high vacuum mechanical booster pumps, staged correctly to achieve sufficient pumping speed while maintaining satisfactory pressure ratio across each stage. These should be backed by primary pumps of sufficient capacity.

Table 1

process type	VD & VOD *or* VD only
heat mass (capacity)	in tonnes of liquid metal
furnace volume	2-3m^3 per tonne
furnace air leakage	<= 1 kg/h (air@20°C) per 10 tonnes
initial pump down time to VD	7 – 10 mins
VD process pressure	0.67mbar / 0.5torr
VD suction capacity	1.0-1.2 kg/h/tonne (air@20°C) *or* 1250-1500 m^3/h/tonne
VD line diameter	800-1000 mm
VD gas dust load to pump system	low
VD gas temperature to pump system	should be <= 60°C
VOD process pressure	80-200mbar / 60-150torr
VOD suction capacity	variable, typically 75 - 150 m^3/h/tonne
VOD line diameter	800-1000 mm
VOD gas dust load to pump system	can be high if filtration is poor
VOD gas temperature to pump system	should be <= 60°C

LIMITATIONS OF WET VACUUM PUMPING FOR DEGASSING

Steam Ejectors

The steam jet ejector has been the mainstay for industrial vacuum pumping systems designed for operation at pressures above 0.7mbar / 0.5torr. The low initial cost and apparent maintenance free operation of this type of pump is well known. Compression ratios as high as 30–40 can be obtained in a single-stage ejector, but efficiency at these high compression ratios is poor; therefore single ejector stages are generally limited to a compression ratio of around 10. Typically, multiple stages of ejectors must be used for practical degassing systems, and a 4-stage system would be typical of the steel degassing installations where final vacuum levels of 0.7mbar / 0.5torr are required. In particular, the steam ejector system installed needs to have sufficient excess capacity to handle the process loads, steam pressure variations and the inevitable loss in performance due to nozzle wear and especially diffuser contamination from the large amounts of dust arising. This contamination has the unfortunate characteristic of forming a hard aggregate inside the ejector which must be mechanically removed on a routine basis. Steam ejectors have served the steel industry well over the years however the issues which are increasingly making users consider dry alternatives can be summarised as:

- cost of the energy required
- cost of maintenance
- cost of waste water disposal
- environmental impact

Liquid Ring Pumps (LRPs)

Large LRPs (or WRPs - water ring pumps) are a very reliable way to generate fast roughing and high capacity backing for large sets of steam ejectors or dry mechanical boosters. They are well accepted in the steel industry as simple, reliable pumps for initial "hogging" and also to run higher pressure processes such as VOD itself. LRPs are inherently quite tolerant of process dust and dirt since these are largely absorbed and flushed out with the contact seal water creating an effluent. They are however power hungry and demand more power as vacuum increases than dry mechanical pumps. The practical limitations associated with the use of water sealed LRPs for steel degassing are:

1) seal water consumption
A typical 4,200 m^3/h LRP may consume up to 10m^3/h water in standard operation (50% recycled) or 20m^3/h water in 'once-through' mode (i.e. no water recycling) and this water will exit straight to the waste water treatment plant. The LRP manufacturer may particularly recommend once-through mode for VOD processes to minimise abrasion and wear inside the pump. The incoming seal water must be clean but the effluent can be very contaminated by the dust from degassing processes - a significant environmental consequence, requiring careful effluent management practices.

2) seal water temperature
Seal water temperature is critical to LRP performance. This is of special concern for VD backing where the LRP must achieve a good ultimate vacuum to avoid presenting the preceeding pumping stages with excessive pressure ratio. LRP manufacturers' specifications are usually based on 15^{o}C seal water temperature which may be unrealistic, and care must be taken to establish the expected performance with the actual water temperature. As the seal water temperature increases so does its vapour pressure which impairs the LRP's vacuum pumping speed and also begins to cause cavitation within the LRP as the inlet pressure drops towards ultimate. Although many manufacturers incorporate anti-cavitation devices, the net result can be loss of pumping speed, cavitation noise and vibration, which in some cases may lead to damage. Where this would have an impact on VD performance this must be dealt with by:
- use of once-through water (a likely requirement anyway)
- chilling the seal water (high plant and energy cost - may not be economic)
- adding an air ejector stage in front of the LRP
- use an additional booster stage in front of the LRP (adds cost and complexity)

DRY MECHANICAL VACUUM PUMPS

Not until the 1970s were very large Roots type pumps, originally developed for conveying of gases at pressures more than atmospheric, modified for use as vacuum boosters in relatively high vacuum industrial applications. Machines of up to 30,000 m^3/h / 18,000 CFM capacity became viable, and this capacity could now match that provided by steam ejector systems if sets of parallel mechanical booster were used in each stage. This is now the standard approach for dry running steel degassing systems [2].

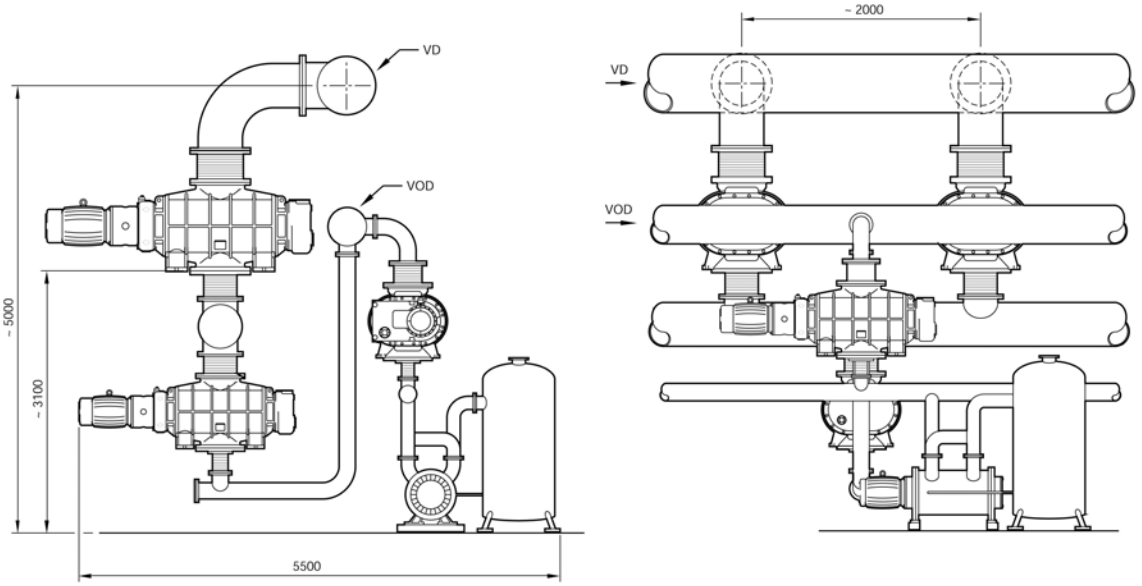
Dry mechanical boosters

The modern, large mechanical booster is a highly cost-effective way of providing large pumping capacity at low pressures, and this technology is especially suited to VD processes. The Roots mechanism when mounted for vertical gas flow is inherently very effective at sweeping larger entrained particulates straight through, while finer dust accumulation can be minimised using appropriate design features. These include adequate shaft seals which avoid any lubricating oil seepage from the gears and drive (since any oil in the swept volume would certainly cause dust accumulation), pressure balancing of the gearbox and drive ends to avoid excessive pressure differential across the seals, and low flow purging to prevent dust penetration through the pressure balancing lines. The use of inverter (variable speed drive) units to control booster motor speeds gives flexibility for starting at higher pressures to provide faster pump down times, and reliability of starting.

It must be remembered that the mechanical vacuum booster is not a true compressor, and always needs a final primary vacuum pump (backing stage) with true compression to vent to atmosphere .

For a typical VD system three stages of mechanical boosters might be used, backed by a suitable primary pump. For VOD at higher pressures only the final booster stage of this system might be needed, backed by the primary pump(s). A typical integrated VD/VOD pumping "module" is illustrated in figure 2. This example shows an LRP used as backing stage, however other backing pumps are discussed below.

Figure 2



Primary vacuum pumping

Oil-sealed primary vacuum pumps are effective and the rotary piston pump type has proved itself good enough to become the metallurgical industry standard for induction melting, precision casting and thermal processing. These processes do generate both metallic and ceramic dusts which can accumulate in the pump sealing oil, causing some wear and performance degradation, but many operators considered the maintenance implications of this to be acceptable, compared to the value of the process. However, this technology could not be justified in the steel degassing industry where product values are relatively low compared to thermal processing and precision casting, and the potential for much larger amounts of dust would add significantly escalated maintenance costs. In both industries the availability of dry vacuum pumps presents opportunities for efficiency improvements and cost savings.

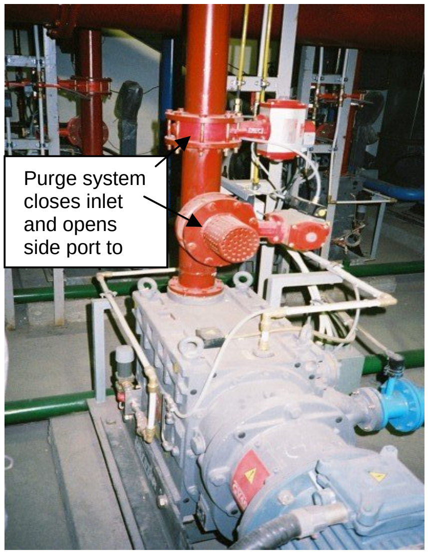
The ideal primary pumping mechanism for backing steel degassing vacuum systems is a dry one in which process dust can be continually swept through without causing an significant damage. There are three major types of dry pump which can be considered: claw, screw and lobe.

Dry claw mechanism

Dry claw pumps have the advantage of generating very high internal turbulence, high internal temperatures and good compression in the gas passing through. This is ideal for most types of potential contamination but is particularly useful when considering the probability of metallic dusts and fines entering the mechanism. Much experience has been gained over the years with this technology, not only in metallurgy but also in other highly dusty and corrosive processes such as semiconductor processing. Good experience in steel degassing installations has been achieved, discussed in more detail below, which demonstrates simplicity of operation and good reliability. Power consumption is also comparatively low towards the ultimate pressures maintained during VD processing, and other utilities consumption is also modest.

In locations where dust loading is extreme, an automated air purge system is useful to provide a momentary high throughput of atmospheric air during normal operation to drive entrained dust out of the pump. This is illustrated on a VD /VOD process in figure 3.

Figure 3



Dry screw mechanism

Dry screw pumps do have the capacity to generate high internal temperatures and good compression, and are useful where entrained liquids or corrosives may be occasionally encountered. However, they are comparatively newer and do not yet have a track record in the industry for handling large amounts of metallic dusts and fines. On this basis they cannot yet be recommended for in steel degassing installations. However, like dry claw pumps the power consumption is comparatively low towards ultimate pressures, and other utilities consumption is also modest.

Dry lobe mechanism

Dry lobe pumps are in effect multi-stage Roots mechanisms and therefore have the Roots advantage being able to pass much contamination straight through. Compression is achieved through the staging (a typical pump would have three reducing stages on a common shaft with intercooling provided). The turbulence generated is be able to deal with most metallic dusts and fines. Much experience has been gained on dirty and corrosive processes with these pumps, and current experience in steel degassing installations with medium dust loads is also good. Power consumption is typically higher towards the ultimate pressures maintained during VD processing.

Large dry exhausters

An exhauster here is a large mechanical Roots type booster modified for direct venting to atmosphere as a primary pump. This differs from a convention mechanical booster in having a stronger construction, built-in gas cooling devices, and a much more powerful motor. These machines are effectively dry alternatives to the LRP, and they can provide big roughing capacity at proportionately lower cost than sets of other dry primary pumps. As single units, exhausters usually have a much poorer ultimate vacuum than LRPs (typically limited to 200mbar / 150torr) which may still be useful for VOD. However, for VD duties two-stage exhauster sets are needed. The ultimates of these two-stage sets are typically better than those of LRPs. The big advantages of dry exhausters compared to LRPs are minimal water consumption (only small quantities needed for cooling) and no major waste water disposal problem, no performance dependence on water temperature, and a good, reliable ultimate pressure. The only drawbacks associated with the use of dry exhausters for steel degassing are:

- they are comparatively more expensive than LRPs
- they generate high noise levels
- their power consumption is higher than LRPs

OPERATING EXPERIENCE

Current operating experience with dry vacuum degassing systems using dry primary pumps is exemplified by the following three case studies. These range from small to reasonably large degassers, and all operate in both VOD and VD modes.

Case Study 1

This is a modern steel degassing plant of nominal 75 tonne heat capacity, designed for VD at 0.67mbar / 0.5torr and VOD in the region of 200mbar / 150 torr. This is a new, relatively compact installation where no provision for steam was made. The outline vacuum system specification is shown in Table 2.

Table 2

heat mass	75 tonnes
system volume	220 m^3 (including cyclone/filter)
VD pressure	0.67mbar / 0.5torr
VD vacuum capacity	80kg/h (dry air 20°C equivalent)
VD process time	~ 20 minutes
VD argon flow	up to 7.5 Nm^3/h
VOD pressure	200mbar / 150torr
VOD vacuum capacity	12,000 m^3/h @ 200mbar
VOD process time	~ 40 minutes
cycles per 8h.	4 / 5
annual production	150,000 tonnes

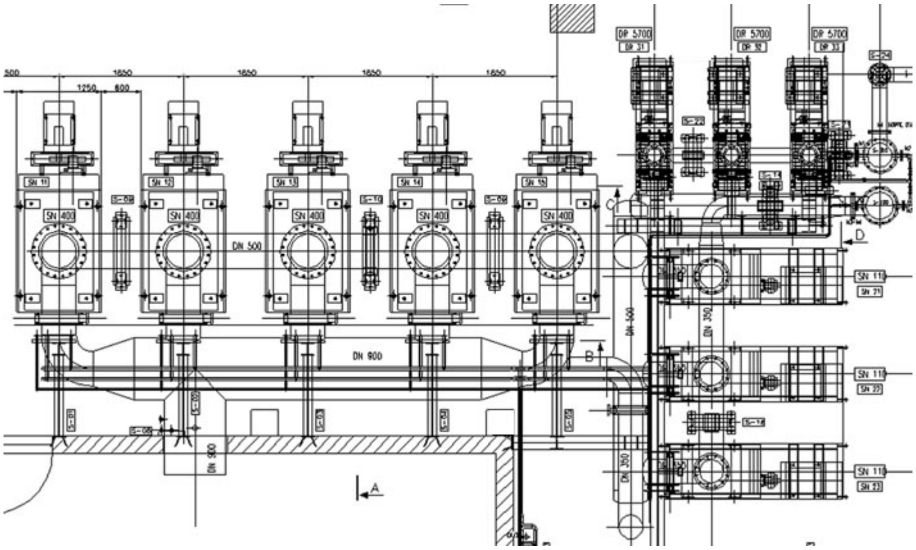
Specifically for the VOD process a large and efficient cyclone/bag filtration system is installed upstream of the vacuum system.

To achieve the required 80kg/h VD vacuum capacity (which equates to ~ 100,000m^3/h at VD pressure) the following 4-stage mechanical vacuum pump system was installed:

Stage 1:	4-off	mechanical boosters, nominal displacement ~30,000 m^3/h each, 45kW motors
Stage 2:	2-off	mechanical boosters, nominal displacement ~14,000 m^3/h each, 75kW motors
Stage 3:	2-off	mechanical boosters, nominal displacement ~5,700 m^3/h each, 55kW motors
Stage 4:	2-off	dry mechanism primary pumps, nominal speed ~1,250 m^3/h each, 30kW motors

The boosters in stages 3 & 4 are run using frequency inverters (variable speed drives) so that they can be safely operated at higher inlet pressures right from the start of the pump down. Stage 1 pumps are switched on at ~ 25mbar / 19torr. For reasons of redundancy, the operator specified that a spare pump is installed, but not normally operated, in each of the four stages. Heat exchangers are included between stages 2 & 3, and 3 & 4 in order to reduce heat load and ensure reliability under all possible operating conditions. A bypass is installed around the stage 1 pumps so that they present no restriction when they are not switched on. Figure 4 shows the very compact arrangement achieved with stages 1, 2 & 3 of this large pumping system.

Figure 4



A typical start sequence at the beginning of the pump down cycle is:
- stage 4 (backing) pumps operating
- main system valve and chamber valves open
- stage 3 & 2 mechanical boosters start on inverters under current control
- VOD process operating
- at 25 mbar the stage 1 by-pass valve is closed, and stage 1 machines start with soft start
- VD process operating

At the end of a cycle, the main chamber valve is closed and the stage 1 pump valves are closed (as are the non-return flaps). In-between heats, there are 3 different volumes kept isolated: the open vessel and cyclone; the isolated filter under a light nitrogen atmosphere; and the isolated pumps under vacuum with the trapped off-gas atmosphere comprising 30-40 % Ar and ~50 % air (from leaks).

Results

In the first year of operation the system is only running VD processes. VOD will begin in the second year of operation. Experience with VD runs exceeds over 100 cycles so far during the extended system evaluation.

1. ultimate pressure achieved

At pump set entry, with stage 1 inlet valves closed, an ultimate pressure of <0.05 mbar / 0.037 torr is consistently achieved. In the degassing vessel, without ladle or argon load, 0.16-0.18 mbar / 0.12-0.14 torr is achieved. When the degasser contains the ladle with steel, and at an argon flow of 4.5 Nm3/h, the ultimate with 4 stage 1 pumps running is 0.25-0.3 mbar / 0.19-0.23 torr. With 5 stage 1 pumps running it is ~0.2 mbar / 0.15 torr. This data confirms the expected gas flows under VD end conditions:- air leak of ~16 Nm³/h (20 kg/h), argon ~7,5 Nm³/h and metallurgical gases (H_2O+CO+H_2+N_2) ~0,5 Nm³/h.

2. empty evacuation time

With the vessel empty, but with commissioning screens in front of each mechanical booster in place, pump down to 0.67 mbar / 0.5 torr is achieved in a fraction over 7 mins. User preference is currently for the screens to remain in place for the time being. Although there is potential to reduce the empty pump down time with the existing system, there is a conflicting requirement for careful control of the pump down to avoid excessive slag foaming.

3. leak rates
The pumping system alone indicates a leak rate of < 1 kg/h. The leak rate for the complete installation is around 18-23 kg/h, mainly due to the oxygen lance lead-through in the vessel cover.

4. slag foaming
Slag foaming in this installation starts at ~100 mbar / 75 torr and continues down to ~ 1 mbar / 0.75 torr. The reasons for the continuous slag foaming here are Zn, Mg and mainly water. Argon injection needs to be stopped completely for some time to prevent overflow of the ladle with a 700-800 mm freeboard. Foaming can also be controlled by using the inverters (VSDs) on the stage 2 & 3 pumps to control system pumping speed directly to prevent over-foaming (the pump speed is matched to the gas load so the vacuum level is held until foaming subsides). The inverters allow pre-programmed ramped control of the pump rotation, or alternatively, manual potentiometer speed control is possible, especially where the degasser is visually monitored by CCTV camera so the operator can control foaming. The inverter method of control also limits power consumption - whereas the use of controlled air bleeds would add to the gas load and increases power consumption during the slag foaming control phase.

5. hydrogen reduction
The product hydrogen values achieved are always below 1.5 ppm, after starting from >4 ppm.

6. power consumption
Power consumption averages per cycle are: 100 amps during 7 minutes evacuation; 35 amps during 20 minutes treatment; overall 35kWh per cycle for the pump system.

7. dust load
For the VD process the dust load averages around 10 litres of material in the filter, and 5 litres in the cyclone per 4 heats. There are no reported problems with residual dust load entering the pump system.

Case Study 2

This is a small steel degassing plant, originally using steam ejectors backed with a liquid ring pump, with a nominal 12 tonne heat capacity. Since degassing was the last process on this site to use steam, and the inefficiencies of the steam ejectors were well appreciated, there was a high level of interest in switching to a dry pumping system. The site operates VD at 0.67mbar / 0.5torr and VOD in the region of 200mbar / 150 torr. The outline vacuum system specification is shown in Table 3.

Table 3

heat mass	12 tonnes
system volume	80 m^3 (including cyclones)
VD pressure	0.6mbar / 0.45torr
VD vacuum capacity	20kg/h (dry air 20^{o}C equivalent)
VD process time	~ 15 minutes
VD argon flow	up to 3 Nm^3/h
VOD pressure	150-350mbar / 112-262torr
VOD vacuum capacity	2,300 m^3/h @ 200mbar
VOD process time	~ 60 minutes
cycles per 8h.	2
annual production	20,000 tonnes

A cyclone separator is installed upstream of the pumping system. For the VOD process the cyclone removes about 70% of the large amount of entrained dust, with the remainder passing through to the water-sealed liquid ring pump (LRP) which was retained. For the VD process, which generates less dust, some of the dust is captured in the cyclone while the rest passes through the two stages of mechanical booster vacuum pumps and then into the dry claw backing pumps. The backing pumps are equipped with automatic air purging systems to prevent excessive dust from building up inside them.

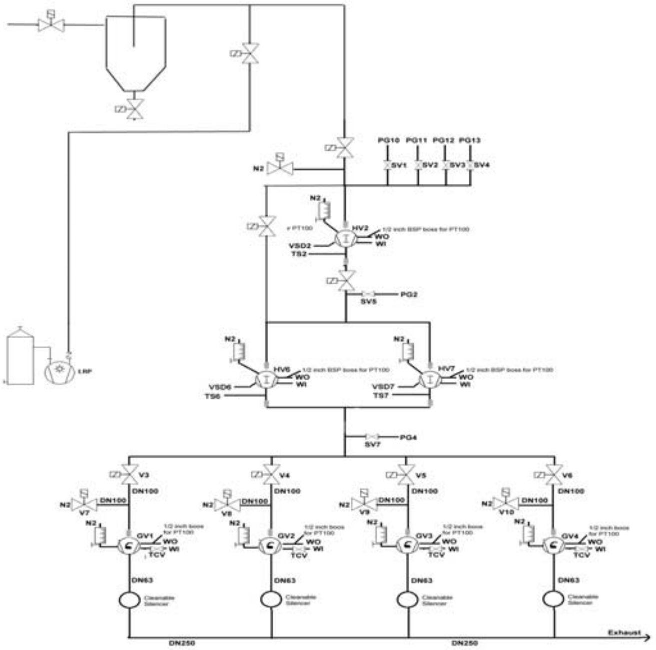
To achieve the required 20kg/h VD vacuum capacity (which equates to ~ 28,000m^3/h at VD pressure) the following 3-stage mechanical vacuum pump system was installed:

Stage 1: 1-off mechanical boosters, nominal displacement ~30,000 m^3/h, 30kW motor
Stage 2: 2-off mechanical boosters, nominal displacement ~4,200 m^3/h each, 11kW motors
Stage 3: 4-off dry claw mechanism primary pumps, nominal speed ~400 m^3/h each, 18kW motors

For the VOD process the separate LRP of nominal 2,500 m^3/h capacity is used. This LRP is also used during initial pump down.

The boosters in stage 2 are equipped the hydrokinetic drives so that they can be safely operated at higher inlet pressures right from the start of the pump down. The stage 1 pump is switched on at ~ 25mbar / 19torr. For reasons of redundancy, the operator requested two additional stand-by pumps to be installed in stage 3. A bypass is installed around the stage 1 pump so it presents no restriction when it is off. Figure 5 shows the general system arrangement.

Figure 5



The pump down cycle is:
- stage 3 (backing) pumps, stage 2 boosters and LRP all operating
- main system valve and chamber valves open
- when 200 mbar / 150 torr VOD pressure reached, LRP is used alone, VD pump system is valved out
- VOD process operating
- after VOD, VD pump system is valved in and LRP is valved out
- at 25 mbar the stage 1 by-pass valve is closed, and stage 1 machines start with soft start
- VD process operating

Results

In two years of operation so far there have been over 3000 VOD + VD cycles.

1. ultimate pressure achieved
At pump set entry, with stage 1 inlet valves closed, an ultimate pressure of <0.1 mbar / 0.075 torr is achieved. In the degassing vessel, without ladle or argon load, 0.2-0.3 mbar / 0.15-0.22 torr is achieved. When the degasser contains the ladle with steel, and at an argon flow of 3 Nm3/h, the ultimate is 0.6 mbar / 0.45 torr. For the VOD process, using the LRP only with seal water temperature at 15^{o}C, a vessel pressure without ladle or oxygen load of ~33 mbar / 25 torr can be achieved. When the degasser contains the ladle with steel, 175 mbar / 131 torr is achieved with an oxygen flow of 400 Nm3/h, and 350 mbar / 262 torr is achieved with an oxygen flow of 800 Nm3/h.

2. empty evacuation time
With the vessel empty, but with protection screens in place, pump down to 0.6 mbar / 0.45 torr is achieved in around 10 mins.

3. leak rates
The pumping system alone indicates a leak rate of < 1 kg/h. The leak rate for the complete installation is around 2-3 kg/h.

4. hydrogen reduction
Hydrogen reduction achieved is consistently more than 4 ppm, with end values below 1.5 ppm. Nitrogen reduction is more than 40 ppm.

5. power consumption
Power consumption averages per cycle are: 14kWh during evacuation to 0.067 mbar / 0.5 torr; 20kWh during VD cycle; 60kWh during VOD cycle.

6. dust load
The VOD process produces up to 180kg dust per cycle, but since this plant uses an LRP with once-through seal water, this dust ends up in the waste water settling ponds. In this location this is regarded as acceptable by the operator. The VD process dust load averages around 60 kg per cycle, and about 18kg of this enters the pumping system. Stage 1 & 2 mechanical boosters have gas purging systems which prevent contamination of gearboxes and bearings, and these boosters have vertical (downward) flow which encourages dust to pass straight through. The stage 3 dry claw backing pumps are able to handle significant dust loads but are also equipped with automated air purge systems. When their motor current exceeds full load the pump inlet is briefly isolated and an atmospheric air purge valve is opened for 1-2 seconds. This blows excess dust out of the pump and into its exhaust. Dust in the exhaust line can then be handled by the EAF dust handling system or trapped in a separate filter.

Case Study 3

An existing steel plant did not have any vacuum degassing facility and required to add it without bringing steam onto the plant. The nominal 95 tonne heat capacity system was to be updated with a dry running mechanical vacuum system. This site also operates VD at 0.67mbar / 0.5torr and VOD in the region of 200mbar / 150 torr. The outline vacuum system specification is shown in Table 4.

Table 4

heat mass	95 tonnes
system volume	170 m^3 (including cyclones)
VD pressure	0.67mbar / 0.5torr
VD vacuum capacity	>80kg/h (dry air 20^{o}C equivalent)
VD process time	~ 20 minutes
VD argon flow	20 Nm^3/h
VOD pressure	100-200mbar / 75-150torr
VOD vacuum capacity	7,000 m^3/h @ 100mbar
VOD process time	~ 30 minutes
cycles per 8h.	4
annual production	200,000 tonnes

An inlet cyclone separator is installed to prevent excessive amounts of dust entering the vacuum pump system. For the VOD process the operator elected to use water-sealed LRPs. However, for the VD process two stages of mechanical booster vacuum pumps with dry claw backing pumps are installed. The backing pumps are equipped with automatic air purging systems to prevent excessive dust from building up inside them.

To achieve the required 80kg/h VD vacuum capacity (~ 100,000m^3/h at VD pressure) the following 3-stage mechanical vacuum pump system was installed:

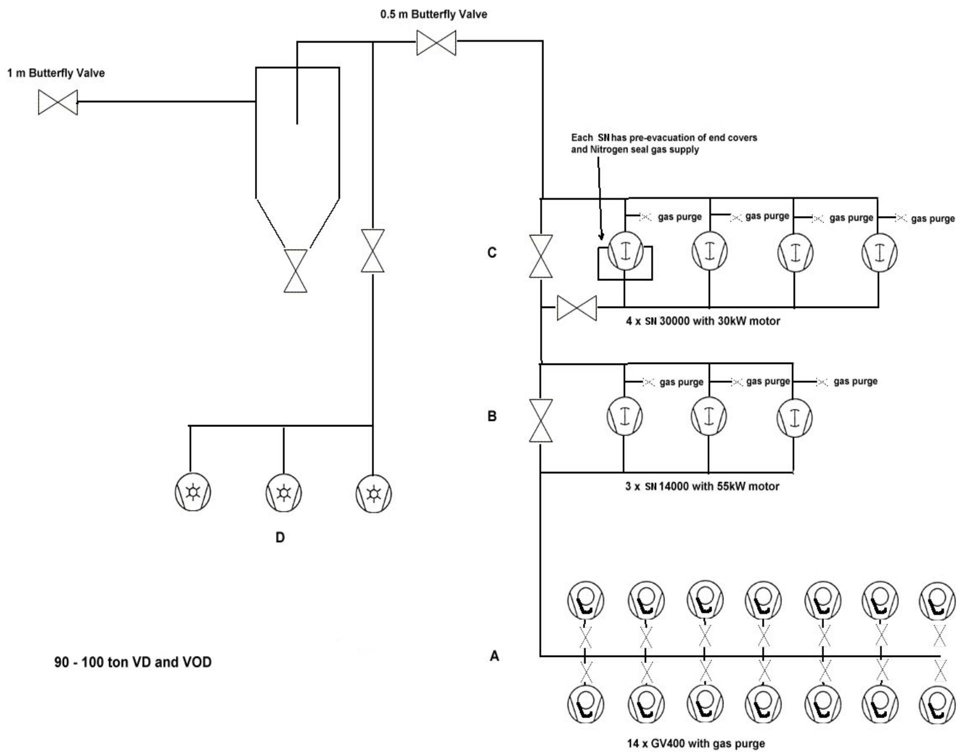
Stage 1:	4-off	mechanical boosters, nominal displacement ~30,000 m^3/h, 30kW motor
Stage 2:	3-off	mechanical boosters, nominal displacement ~14,000 m^3/h each, 55kW motors
Stage 3:	14-off	dry claw mechanism primary pumps, nominal speed ~400 m^3/h each, 18kW motors

Three separate LRPs of nominal 2,500 m^3/h capacity are used in parallel for VOD, and these pumps also assist the initial pump down.

The boosters in stages 1 & 2 are equipped the inverter (VSD) drives to give soft starting after the end of the VOD phase. Bypasses are also installed around the stages 1 & 2 so no restrictions are presented during VOD. Figure 6 shows the general system arrangement.

The pump down cycle is:
- stage 3 (backing) pumps, and LRPs all operating
- stage 1 & 2 bypasses open, 0.5m butterfly valve is closed
- main LRP valve and chamber valves open
- when 800 mbar / 600 torr is reached, butterfly valve is opened and stage 3 pumps assist pump down to ~ 200 mbar / 150 torr. The butterfly valve is then closed and VOD runs into the LRPs alone
- after VOD, LRP valve is closed and LRPs are shut down. Butterfly valve is opened again, stage 2 bypass is closed and stage 2 & 3 pumps take the process down to 20 mbar / 15 torr
- at 20 mbar / 15 torr stage 1 by-pass valve is closed, and stage 1 machines start with soft start
- VD process operating at 0.67 mbar / 0.5 torr

Figure 6



Results

In nine months operation there have been more than 400 VOD + VD cycles.

1. ultimate pressure achieved
At pump set entry, with stage 1 inlet valves closed, an ultimate pressure of <0.1 mbar / 0.075 torr is achieved. In the degassing vessel, without ladle or argon load, 0.2-0.3 mbar / 0.15-0.22 torr is achieved. When the degasser contains the ladle with steel, and at an argon flow of 20 Nm3/h, the ultimate is 0.6 mbar / 0.45 torr. For the VOD process, using the LRPs only with seal water temperature at 15^{o}C, a vessel pressure without ladle or oxygen load of ~33 mbar / 25 torr can be achieved. When the degasser contains the ladle with steel, 100 mbar / 75 torr is achieved with an oxygen flow of 1000 Nm3/h, and 200 mbar / 150 torr is achieved with an oxygen flow of 1500 Nm3/h.

2. empty evacuation time
With the vessel empty, but with protection screens in place, pump down to 0.67 mbar / 0.5 torr is achieved in around 5 mins.

3. leak rates
The pumping system alone indicates a leak rate of < 1 kg/h. The leak rate for the complete installation is around 28-30 kg/h.

4. hydrogen reduction
Hydrogen reduction achieved is greater than 4 ppm, with end values below 1.5 ppm. Nitrogen reduction is better than 40 ppm.

5. power consumption
Power consumption averages per cycle are: 19kWh during evacuation to 0.067 mbar / 0.5 torr; 70kWh during VD cycle; 125kWh during VOD cycle.

6. dust load
The VOD process produces up to 1400kg dust per cycle, of which an estimated 400kg per cycle goes through the LRPs (using once-through seal water) and ends up in the waste water settling ponds. The VD process dust load averages around 450kg per cycle, and about 140kg of this enters the pumping system. Stage 1 & 2 mechanical boosters have gas purging systems which prevent contamination of gearboxes and bearings, and these boosters have vertical (downward) flow which encourages dust to pass straight through. The stage 3 dry claw backing pumps are fully equipped with automated air purge systems as before. Dust blown through into the exhaust line can then be handled by the EAF dust handling system.

Summary

Current experience confirms the effectiveness and reliability of dry mechanical vacuum pump systems for VD processes in particular. In all cases even significant dust loads can be handled, however the use of effective cyclone and filtration systems in front of the vacuum pumps will ensure that dry dust can be collected for disposal in a convenient location. This can be important for plants where maximum material recycling is an issue.

OPERATING COST COMPARISONS

It is clear that all-dry mechanical vacuum pumping systems operate successfully on steel degassing duties and it is also clear there are significant operational cost savings using mechanical pumps in place of steam ejectors. Table 5 reflects a typical comparison of the operational costs associated with steam ejector use against those arising from modern dry mechanical vacuum pumps for a small 50 tonne ladle size being operated on VD with a 20 minute cycle at 50,000 tonnes/year (data from Hick Hargreaves & Co and V.V. Fondrik [3]).

SUMMARY

Based on the evidence of the user’s experience over the past four years we can conclude the use of mechanical vacuum pumps to replace steam ejectors is a viable option and offers some significant advantages. The biggest of these is the saving in power use and operating costs. Greater than 90% of the operating costs can be saved by using mechanical pumps in place of steam ejectors. Using entirely dry running (with no vacuum pump seal fluids) has further advantages with regard to the amount of wet effluent generated, and this brings additional environmental benefits. Whilst the initial capital cost of mechanical pumps can be around double the cost of a new steam ejector system and boiler, the payback even on a moderate production quantity can readily be justified, particularly when typical 10 year life cycles are considered for VD / VOD installations. This consideration excludes the hidden costs of routine boiler certification and maintenance, and the need to retain qualified boiler operators.

Reliability has also been effectively demonstrated, and designs for gas path and pump purging have ensured dust does not cause problems, with any residual dust collecting in the pipe work being easily be removed with a vacuum cleaner through the access ports placed at appropriate points. By contrast the dust accumulations in steam ejector pipe work (where dust combines with water to form a cement like deposit) always require significant efforts to clean.

Table 5

	Costs	**Steam Ejectors**	**Ejectors w/LRP**	**Ejectors w/LRP & dust trapping**	**Dry Pumps &dust trapping**
Utilities					
steam	$30.0/t	$1.40/t	$1.10/t	$0.80/t	
condenser/seal water	$0.04/m^3	$0.12/t	$0.11/t	$0.08/t	
pump cooling water	$0.03/m^3				$0.002/t
compressed air	$0.02/m^3				$0.001/t
nitrogen	$0.1/m^3				$0.010/t
gear oil	$12/litre				$0.002/t
electricity	$0.05/kWh	$0.05/t	$0.13/t	$0.13/t	$0.08/t
Maintenance					
nozzle cleaning	$800/outage	$0.08/t	$0.08/t		
heat exch. cleaning	$250/service				$0.005/t
filter cleaning	$375/service			$0.03/t	$0.03/t
dust disposal	$100/t	$0.01/t	$0.01/t	$0.01/t	$0.01/t
sludge disposal	$1.8/m^3	$0.04/t	$0.04/t		
Spares					
filter bags	$1200/set			$0.012/t	$0.012/t
operating cost/tonne		$1.70/t	$1.47/t	$1.06/t	$0.15/t
total operating cost		$85,000	$73,500	$53,000	$7,500
annual saving with dry pumps		**$77,500**	**$66,000**	**$45,500**	

Finally we can conclude that the mechanical pump systems offer a more consistent process vacuum, usually at better levels than steam ejectors actually achieve, while providing reliable on-demand operation with zero power consumption during idle periods. A range of standard dry pumping packages especially suited to "mini-mill" sized plant (e.g. 30-150 tonnes heat capacity) are currently available.

REFERENCES

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3. V. V. Fondrik, “The steam jet ejector: a versatile pump for high vacuum”, Elliott Company, Jeannette, Pennsylvania