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RECENT DEVELOPMENTS AND EXPERIENCES IN MODULAR DRY MECHANICAL VACUUM PUMPING SYSTEMS FOR SECONDARY STEEL PROCESSING

OSTATNIE OSIĄGNIĘCIA I DOŚWIADCZENIA Z MODUŁOWYMI SUCHYMI MECHANICZNYMI POMPAMI PRÓŻNIOWYMI DLA WTÓRNEJ RAFINACJI STALI

As the world wide demand for speciality steels continues to increase, significant attention is focused on the VD and VOD processes, with an increasing emphasis on lowering energy consumption, improving production rates, ensuring environmental compliance, and reducing greenhouse gas emissions. The combination of ladle tank installations having low leak rates with specialised, high capacity, dry mechanical vacuum pump systems now enable an integrated and optimised vacuum degassing station design, precisely specified for the needs of the process. High efficiency, 3-stage vacuum pump modules provide the required pumping capacity to suit the process together with a very economical power demand and a low consumption of utilities. Key features are the good operational flexibility of such installations and the integration of pump control, using variable frequency drives for each pump, directly into the control system. Overall efficiency is maximised and operating energy savings of up to 90% or more can be achieved, compared to conventional steam ejector-based systems. Additional major benefits are significant reduction in green house gas emissions and reduced effluent disposal costs.

Keywords: Vacuum degassing; VD; VOD; mechanical vacuum pumps; modular systems; energy efficiency; environmental impact; reduced emissions; control optimisation; slag foaming; operational flexibility; metallurgical quality

Aktualnie dostrzegalny jest wzrost światowego zapotrzebowania na specjalne gatunki stali. Wpływa to na coraz większe zainteresowanie procesami VD oraz VOD. Związane jest to z dążeniem do zmniejszenia zużycia energii, podwyższeniem jakości produkcji oraz chęcią ochrony środowiska, a zwłaszcza ograniczeniem emisji gazów cieplarnianych. Połączenie starej oraz nie zawsze szczelnej instalacji odgazowania stali z bardzo wydajnym systemem suchych mechanicznych pomp próżniowych pozwala zoptymalizować prace stanowiska pomp, dostosowując precyzyjnie do potrzeb procesu. Wysoka sprawność 3 stopniowych modułów pomp próżniowych zapewnia wysoką wydajność, łącznie ze zmniejszeniem zapotrzebowania na energię oraz małego zużycia urządzeń. Jedną z ważniejszych cech takich układów jest elastyczność oraz możliwość sterowania zintegrowanego pomp, przy użyciu silników zmiennej częstotliwości dla każdej pompy indywidualnie, bezpośrednio włączonych do systemu sterowania. Osiągnięta wysoka wydajność stwarza możliwość zaoszczędzenia nawet do 90% energii w porównaniu z tradycyjnym systemem "smoczków" parowych. Dodatkową korzyścią jest ograniczenie emisji gazów cieplarnianych oraz ograniczenie wydatków na odprowadzenie dużej ilości ścieków przemysłowych.

1. Introduction

The current high level of demand for steel around the globe, especially driven (according to many observers) by the growing and renewing economies of China, India, Russia, Eastern Europe and elsewhere, is placing a world-wide premium on steel production in general. With the particular expansion of oil pipelines, gas distribution networks and railways in many places, the market for speciality degassed steels also continues to increase. To meet these needs, and other new market opportunities for ever higher steel quality and performance, significant attention now appears to be focused on secondary steel processing, and on the vacuum degassing (VD) and vacuum oxygen decarburisation (VOD) processes in particular. This is against a backdrop of increasing emphasis, in many steel plants, on the following critical issues:

a. lowering the energy consumption – where previously the continuous consumption of huge amounts of hydrocarbon fuels in order to continuously generate steam as a process utility was regarded as a norm, the ever increasing cost of fuels is now forcing a much closer evaluation of the real need for steam generation on many plants.

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b. improving production rates – VD and VOD are batch processes, traditionally done intermittently. However the increasing value of the secondary steel product resulting, coupled with the need to increase plant efficiency and maximise revenues, means that more frequent cycles are being required, with correspondingly less time allowable for maintenance and unplanned outages. In contrast, tighter control, licensing and insurance for boiler installations can all place added cost burdens and operational restrictions on the availability of process steam to run vacuum ejector systems.
c. improving safety – the traditional use of high pressure stream to power steam vacuum ejectors is coming under increasing scrutiny, especially in view of the risks associated with high pressure piping and pressure vessels, high temperature fuel distribution systems and burner installations. The long start-up and shut-down times for such systems also present limitations on safe working flexibility.
d. ensuring environmental compliance – air pollution regulations are becoming more stringently applied in many places, and in particular the control of toxic and acid rain emissions from combustion processes (such a steam raising) is expected to put continued pressure on steel plant operators in the future.
e. reducing greenhouse gas emissions – the Kyoto Protocol in 1992 established the commitment to reduce greenhouse gas emissions in order to combat global warming, and a principle target is the reduction of carbon dioxide emissions from combustion processes. This issue remains in universal focus and, through the various carbon-trading fiscal mechanisms now arising, provides an additional impetus to minimise the use of steam-generating boilers wherever possible.

Steel plant operators are now being able to address all of these issues using integrated VD and VOD ladle tank vacuum stations for preparing degassed steels. The combination of new generation ladle tanks with excellent, low leak rates, together with recent developments of specialised, high capacity, dry mechanical vacuum pump modules with near-instantaneous start-ups and shut-downs, now enable an integrated and optimised degassing station design to be achieved, precisely specified for the actual metallurgical needs of the process, and completely free from any requirement to consume steam as a utility.

2. Basic system parameters

Various general reviews of secondary steel processing have been published or are available from commercial sources, however a good introduction is provided by Shoop [1]. The essential objective is the purification of the steel by removal under vacuum of light metal and gaseous impurities (especially hydrogen and nitrogen), assisted by argon purging (or "stirring"), and also assisted by chemical interactions with the slag layer. The conventional "optimum" vacuum level to be attained in the VD process is usually given as 0.67 mbar (hPa), but in any case excellent results can also obtained above this pressure since the degassing process is also influenced by many other factors, including argon stirring rate and time.

In all cases where mechanical vacuum pumps are to be used it is firstly essential to ensure a suitable cyclone/bag filter unit is installed between the ladle tank and the vacuum pumps, to protect the pumps from an excessive dust burden. In general, such bag filter units should be capable of handling the specified pumping speed curve of the pump set, across the whole pressure range, and should have a minimal pressure drop characteristic. A figure of 0.10 – 0.15 mbar (hPa) pressure drop at the 1 mbar (hPa) operating pressure region should be achievable. The residual dust slippage through the cyclone/filter should be ideally less than about 50 mg/m^3. Since the metallurgical gases being pumped through the system may contain intermittent traces of hydrogen coming from the steel it is essential that only inert purge gases (e.g. nitrogen) are used for any vacuum pump seal purges, and also that the final exhaust chimney vents to a safe outside area where there is no risk of any possible ignition sources.

The sizing of the vacuum pumping system needed derives both from experience and from basic theoretical considerations of the process. In principle, the gas load to the vacuum pumps may simply be considered to comprise:

a) metallurgical hydrogen
b) metallurgical nitrogen
c) carbon dioxide (reaction of metallurgical carbon and metallurgical oxygen)
d) argon injected for stirring
e) air leakage into the system

The masses of each metallurgical gas evolved during the process may be estimated from the mass of the steel, and the starting and ending gas concentration levels. These masses can then be related to a mass flow rate for each, according to the duration of the process (typically 20 minutes), and then a volume flow rate for each at the nominal end vacuum level of 0.67 mbar (hPa) can be calculated. The argon stirring rate is a known parameter for each system, and can be converted into a volume flow rate at end vacuum level. Similarly, the air leak rate of the system should be measured routinely and converted on the same basis. In a well-designed, well-maintained modern ladle tank the leak rate should certainly be below 20 kg/h. The sum of the flow rates can then be used to define the nominal pumping capacity required.

It has previously been noted [3,4] that this produces an interesting relationship. Using typical operational parameters it is found that approximately 1,250 m^3/h pumping speed at 0.67 mbar (hPa) is required per tonne of heat mass in a typical VD process, which equates to a mass flow equivalent of about 1.0 kg/h (air at 20°C) per tonne at that pressure. Recent results with even very large systems (up to 100 tonne heat mass) and mechanical vacuum pumps confirm this relationship and demonstrate excellent metallurgical quality can be achieved down to 0.5 ppm H. This compares very favourably with typical steam ejector installation parameters which traditionally specify requirements of up to 2.4 kg/h (air at 20°C) per tonne at 0.67 mbar (hPa). This will be further explored below.

3. Survey of recently operating plants

Table 1 below provides an outline summary of some recent dry mechanical vacuum pumping installations on steel degassers processing heat sizes above 20 tonnes [2]. This amply serves to illustrate the recent increases in demand for such systems, and also shows an interesting geographical bias to regions where, not only is secondary metallurgy technology well developed, but also where investment (for medium-size plants at least) is clearly taking place.

TABLE 1
Recent operating dry mechanical vacuum pump systems for vacuum degassing

Year commissioned	Country	Heat size (tonne)	Peak suction capacity (m^3/h)	Primary pump type
2001	Moldova	95	98,000	dry claw
2002	Italy	75	98,000	tri-lobe Roots
2003	Italy	42	45,000	dry claw
2004	Switzerland	75	104,000	tri-lobe Roots
2004	Germany	80	105,000	dry screw
2005	Italy	42	40,000	dry screw
2006	USA	41	87,000	dry screw
2006	Ukraine	100	145,000	dry screw
2006	Italy	53	52,000	dry screw
2006	Spain	42	35,000	dry screw
2006	Turkey	100	120,000	dry screw
2006	Turkey	90	116,000	dry screw
2007	Turkey	70	80,000	dry screw
2007	Italy	90	120,000	dry screw
2007	Ukraine	60	87,000	dry screw
2007	Italy	90	87,000	dry screw
2008	Romania	100	116,000	dry screw

4. Modular dry mechanical vacuum pumping system

The basic requirement for good degassing of steel under vacuum therefore is to be able to hold the liquid steel at a pressure at, or below, 1 mbar (hPa) for a period of around 15 – 20 minutes while at the same time purging (or “stirring”) the liquid steel with argon to carry away the impurities. Of course it is also vital to maintain the correct chemistry of the slag layer on top of the steel to meet the metallurgical requirements for the steel batch. It is also important to avoid any loss of the slag from the ladle due to foaming and spillage which could occur. Under these conditions it could be expected that significant reduction in residual hydrogen level in the metal can be achieved and, by convention, the residual hydrogen measurement in the processed steel is a primary indicator of the success of the processing and the quality of the resulting product. In the latest installations, residual hydrogen content in the product steel may be consistently reduced to around 1 ppm, or less. This means that the vacuum pumping system must be able to evacuate the ladle tank from atmospheric pressure down to around 1 mbar in a short time (typically around 6-8 minutes is desired) to avoid unnecessary cooling of the steel, but also to be able to carefully control the rate of pressure descent across the 100-20 mbar (hPa) region, if required, to avoid slag foaming. In other words, the applied suction capacity must be adequate across the pressure range, and the overall pumping speed produced must also be able to be easily and quickly controlled at any pressure.

The configuration of the simplest ideal vacuum pumping system to attain below 1 mbar (hPa) and to comply with these requirements is a 3 stage configuration, and initial exploitation of customised vacuum pumping systems of the 3 stage type was reviewed by the authors [3, 4]. However, more recently the suitability of more standardised, modular pumping systems, optimised for the steel degassing processes, has been recognised. This has been driven by many practical considerations, in particular the desire to refine the pumping system to meet the exact needs of the process, to improve the efficiency of power consumption, minimise utility consumption, and to improve the ease and speed of installation and commissioning. This has resulted in the development of the steel degassing pump module, which is a fully integrated, 3-stage pump system on a transportable skid, for the VD and VOD processes in particular. In order to achieve this, careful consideration of the type and characteristics of the pump for each pumping stage had to be made, in order to ensure each pump is optimal for the duty conditions of that stage.

The function of stage 1 (at the inlet of the pumping system) must be to provide a high suction capacity under good vacuum conditions, and a large Roots-type vacuum mechanical booster pump is ideal for this duty. The unit selected for stage 1 of the modular degassing system is an "HV" (high vacuum) booster type of 36,000 m^3/h nominal displacement, which is characterised as a heavy duty machine with high efficiency, requiring only a 30 kW motor to power it, and configured with appropriate safety purge facilities to protect its bearing and gearboxes from any ingress of process gas or dust. As incorporated into the steel degassing module and backed by the stage 2 and primary (stage 3) pumps, the HV booster provides a peak volumetric efficiency of around 80% and so produces a typical net pumping speed of 29,000 m^3/h at around 0.67 mbar (hPa), as indicated in Fig. 1.

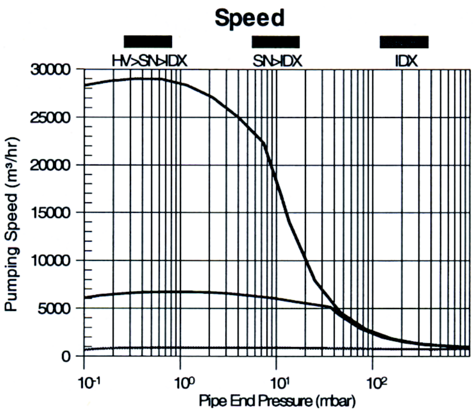

Fig. 1. The speed curves of each stage of the optimised 3-stage vacuum pumping system

The unit selected for stage 2 of the modular degassing system plays an important role not only in providing a good pumping speed at high vacuum to support the stage 1 booster, but also in providing a strongly increasing pump speed during the middle stages of the pump down. For this reason a Roots-type vacuum booster with a capability to provide a high compression ratio at intermediate vacuum levels is ideal, and for this reason the type "SN" mechanical booster is chosen. This machine has a very strong construction, is designed with more "open" rotor-to-stator clearances, and can accommodate higher motor powers (typically 30 kW up to 55 kW is used) which generate higher compression than more conventional vacuum boosters of this size. The "SN" booster has a nominal displacement or 8640 m^3/h and in the steel degassing module it also provides a volumetric efficiency of up to 80%, depending on configuration. It is also configured with the required safety purge facilities.

The "primary" vacuum pump of any system is the pump which finally exhausts the pumped gases to atmospheric pressure, and by definition this is a mechanism with a very high compression. While the key advantage of most "Roots" type mechanical vacuum boosters (as used in stage 1 and 2 positions) is the ability to sweep reasonable amounts of residual process dust through without problem, the more complex mechanism of a primary pump can present more difficulties when it comes to handling amounts of residual dust from the steel degassing process. Such demands are exacerbated in the extreme if a dry mechanism is not used, as any oil-wetted vacuum pump mechanism will suffer significant contamination and degradation on the VD process. For this reason the primary pump for the stage 3 position in the steel degassing module must be a very robust, dry running type with an excellent resistance to dust wear. As illustrated in Table 1, both dry claw and dry tri-lobe types have been successfully applied to steel degassing, however it is clear that the ideal pump should be as large as practical, and the latest generation of large dry screw pumps, with high pumping speeds and excellent resistance to dust, represent the ideal refinement for the optimised pumping module. Therefore the ideal type selected for the steel degassing module is the large "IDX" double-ended variable pitch screw design, conferring the benefits of high pumping speed, excellent reliability and good tolerance to dust contamination. This provides a relatively flat "backing" speed curve of nominally 1000 m^3/h (or optionally 1300 m^3/h) behind the stage 2 SN booster.

Overall controllability of the applied pumping speed is an important issue, as previously mentioned, and the use of electronic variable frequency drives to control all of the motors attached to the pumps produces significant benefits in this respect. In particular it allows the stage 1 and stage 2 boosters to begin operating slowly at relatively high system pressures at the start of the tank pump down, and then allows them to steadily accelerate and provide increasing pumping speed, up to safe motor limits, as the system pressure drops. This gives maximum pumping efficiency, optimises energy use, and allows the pump down to proceed in the most effective way. Furthermore, it allows the plant control system to directly interact with the booster pumps and rapidly effect changes to the overall pumping speed as demanded by the operator in response to the conditions inside the ladle tank during and in particular any incidence of slag foaming.

The resulting steel degassing module is illustrated in Fig. 2. It is optimised for efficiency, performance and simplicity, and represents a refined and highly effective approach to providing the required vacuum pumping speed to the vacuum degassing process. In addition to the practicality of having a compact, space-saving module which is delivered fully piped, wired and instrumented, and which only needs to be mounted in place and connected to the process inlet manifold, exhaust manifold and utilities, the modular concept also gives significant flexibility. This is because a suitable number of modules can be installed in parallel to provide a specific pumping capacity for current requirements, and then increased pumping capacity can easily be provided later if heat sizes are to be increased by mounting additional modules in parallel.

Fig. 2. Three-stage, dry mechanical vacuum pump module for steel degassing

Based on current experience and the considerations in section 2 above, some typical relationships between plant size, system parameters and appropriate numbers of standard pumping modules for the ladle tank VD process are given in Table 2.

TABLE 2

Typical relationships between parameters for modern ladle tank vacuum degassers (VD process) and suitable numbers of vacuum degassing modules

Heat size (tonnes)	Peak suction capacity needed (m^3/h)	Typical system total volume (m^3)	No. of std. pumping modules
23	29,000	65	1
46	58,000	130	2
69	87,000	195	3
92	116,000	260	4
115	145,000	325	5
138	174,000	390	6
161	203,000	455	7

5. Cost savings

A key feature of the modular 3-stage steel degassing system is the potential for significant operational cost savings compared to the use of conventional steam ejectors. The specification for a typical new and efficient steam ejector system for a 135 tonne ladle tank degasser provides a pumping capacity of 330 kg/h (air 20°C equivalent) at 0.67 mbar (hPa), and is designed to consume around 2500 kg steam per VD cycle (around 18.5 kg steam per tonne). In contrast, older steam ejector systems may actually require 40-50 kg/h steam per tonne, or more. The typical steam ejector design capacity allows around 2.4 kg/h pumping capacity per tonne of steel, and

Melt Mass (tonnes)	60	OPERATING COST COMPARISON
Production tonnage	300,000	DRY MECHANICAL VACUUM PUMPS
Cycle Time in vacuum (mins)	20	vs.
Boiler size (kg/h)	6000	STEAM EJECTORS
Process	VD	

Cost criterion		Condition	Specific cost	Steam Ejectors		Dry running pumps including filter operating costs	
Consumption							
- steam		12 bar, 194°C	20.00 €/t	33.3 kg/t	0.6666667 €/t		
- contact water		3 bar, 32 °C	0.04 €/m³	2.7 m³/t	0.1066667 €/t		
- non-contact water		4 bar, 32 °C	0.03 €/m³			0.0700000 m³/t	0.0021000 €/t
- compressed air		5 bar	0.02 €/m³			0.0002000 m³/t	0.0000040 €/t
- nitrogen		5 bar	0.10 €/m³			0.0440000 m³/t	0.0044000 €/t
- gear box oil			3.00 €/litre			0.0004400 litre/t	0.0013200 €/t
- power(pumps+auxiliaries)			0.05 €/kWh	0.33 kWh/t	0.0166667 €/t	0.3000000 kWh/t	0.0150000 €/t
Subtotal consumption					0.7900000 €/t		0.0228240 €/t
Maintenance	**€ per hour**	**man hours**					
- pump service	30.00	4	120.00 €/pump	5000 tappings	0.0007200 €/t	5000 tappings	0.0036000 €/t
- pump cleaning	50.00	40	2000.00 €/job	200 tappings	0.1666667 €/t		
- heat exchanger cleaning	30.00	12	360.00 €/job			5000 tappings	0.0000002 €/t
- filter bag changing	30.00	8	240.00 €/job			1667 hours	0.0000014 €/t
- dust disposal			0.00 €/t	0.00 kg/t	0.0000000 €/t	0.20 kg/t	0.0000000 €/t
- contact water disposal			1.00 €/m³	0.27 m³/t	0.2666667 €/t		
Subtotal maintenance					0.4340533 €/t		0.0036017 €/t
Spares	**€ each**	**number**					
- filter bags	15.00	216	3240.00 €/change			0.0000000 sets/ton	0.0000000 €/t
- seals and bearings	2000.00	per installed pump		2 pumps	0.0060000 €/t	9 pumps	0.0300000 €/t
Subtotal spares					0.0060000 €/t		0.0300000 €/t
TOTAL					1.2300533 €/t		0.0564257 €/t
Difference					0.0000000 €/t		1.1736277 €/t
Annual saving						Saving	352 k€

Fig. 3. Typical operating cost comparison of dry mechanical vacuum pump module with steam ejectors for a nominal 60 tonne VD process

this appears to include a historical capacity excess to allow for routine degradation of ejector performance due to fouling with dust deposition between ejector cleaning operations. As noted above, the true metallurgical, argon and air leakage flow rates from the process would actually imply a capacity requirement of around 1.0 kg/h per tonne, and this is certainly borne out in recent experience with dry mechanical pump systems. This means that ejector systems are not only typically more costly to operate in energy terms, but also appear to be frequently oversized for the duty.

To summarise in overall terms, the higher cost of energy involved in steam generation, the routine maintenance requirements for ejector cleaning, and the higher demand for water with ejector systems (plus the disposal costs of contaminated waste water) all contribute to an increase net operating cost compared to modular mechanical pump systems. A typical operating cost comparison is shown in Fig. 3 which illustrates such potential annual cost saving projections when dry pumps are used.

6. Summary

The high efficiency, 3-stage design of vacuum pump module provides the required pumping capacity and operating pressure requirements to suit the VD and VOD processes, together with a very economical power demand and a low consumption of utilities. The modularity of the design also allows easy installation, fast commissioning, and complete future expandability and effective "future-proofing" of the installation. This system is especially ideal for compact EAF installations but is also suitable for larger degassing plants, remaining economic typically up to 175 tonnes heat mass. The good operational flexibility of such installations and the integration of pump control, using variable frequency drives for each pump, directly into the control system, provides "vacuum on demand", excellent controllability especially for dealing with slag foaming, and enables consistent performance and proven, high quality metallurgical results. Overall system efficiency is maximised and such dry mechanical pumping systems can provide operating energy savings of up to 90%, or more, compared to steam ejector-based systems. Additional major benefits are significant reduction in green house gas emissions, reduced effluent disposal costs, and the elimination of regular steam ejector maintenance. Field experience shows rapid commissioning and start-ups are achievable, and the rapidly-growing numbers of operating degassing plants around the world using dry vacuum pumping systems demonstrates the effectiveness of this technology.

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