SECONDARY STEEL PROCESSING UNDER VACUUM - REDUCING THE ENERGY DEMAND AND THE ENVIRONMENTAL IMPACT

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ABSTRACT

The global steel industry operates in a changing world where there is now an increasing emphasis on lowering energy costs, reducing greenhouse gas emissions, ensuring environmental compliance, and improving production efficiency. These commercial and environmental pressures now apply equally to secondary steel processes such as VD and VOD. New technology integrated ladle tank vacuum degassing stations, equipped with the latest modular dry vacuum pump systems, can provide significant economic and environmental benefits to the operator. The high efficiency vacuum pumping module provides a very flexible and low cost approach to achieving the required performance, with a very economical power demand and a low consumption of utilities. The avoidance of steam use ensures complete elimination of boiler emissions. The modularity of this approach also allows complete future expandability and effective "future-proofing" of the installation. Key benefits are improvements in efficiency and operating energy savings of up to 90% or more, compared to steam ejector systems, significant reduction in green house gas emissions, reduced effluent disposal costs, excellent operational flexibility, and full integration of pump control directly into the control system to provide a true "vacuum on demand" plant.

KEYWORDS

vacuum degassing, energy saving, emissions reduction, greenhouse gas, cost saving, modular system

INTRODUCTION

The demand level for steel around the globe is especially driven by the growing and renewing economies of China, India, Russia, Eastern Europe and South America, and despite the recent economic fluctuations and their affect on steel prices, the underlying long term demand trend remains significantly positive. The ever-present need to re-vamp and expand oil pipelines, gas distribution networks and railway infrastructure, plus the demands of other high performance steel markets, is expected to ensure that the market for speciality degassed steels will continue to remain profitable. To meet these needs significant attention is focused on developing secondary steel processing, and on the vacuum degassing (VD) and vacuum oxygen decarburisation (VOD) processes in particular.

However, there are additional factors which must also be considered. There is an increasing focus on reducing energy usage, especially given the significant rises in the cost of oil and gas, and the prevailing vulnerability of supply, especially in some regions. Then there is the question of the global environmental impact of the steel industry, and in particular the commitments of many nations, now including the USA, to seriously address concerns about climate change and to reduce their emissions to atmosphere of carbon dioxide (CO_2), the most important greenhouse gas (GHG). While GHG emissions are an urgent consideration, steam generating boilers used for traditional stream ejector vacuum systems also generate emissions of hazardous air pollutants, further adding to the complexity of the regulatory regimes under which the steel degassing plant must operate.

For these reasons the following issues are becoming increasingly important in many steel plants:

Reducing energy consumption

While once the continuous consumption of huge amounts of hydrocarbon fuels was regarded as a norm, the ever increasing cost of fuel means that energy costs are now becoming a very significant operating expense. Total energy audits of energy-intensive steel processes are becoming more important (for example, the recent EAF investigation by Holmes et al [1]). As a consequence, alternative methods and technologies with reduced energy requirements are being considered, and the need for steam generation itself is now coming into question on steel degassing plants (authors [2]).

Reducing greenhouse gas emissions

The United Nations Framework Convention on Climate Change (UNFCCC), opened for signature at the Rio Earth Summit in 1992, established a global commitment to reduce GHG emissions in order to combat global warming. A principle target of the convention is the reduction of CO_2 emissions from industrial plants, and from combustion processes in particular. The subsequent Kyoto Protocol of 1997 formulated an international agreement with binding emissions targets. This issue remains in universal focus and, through the various emissions reduction initiatives and carbon-trading fiscal mechanisms now in place, provides a strong impetus to minimise CO_2 emissions from steel plants.

Ensuring environmental compliance

Air pollution regulations are becoming more stringently applied, and in particular the need for tight control of toxic and acidic gas emissions (the so-called hazardous air pollutants - HAPs) from combustion processes, such as steam-raising, is putting continued pressure on steel plant operators.

Improving safety

The traditional use of high pressure steam to power vacuum ejectors is coming under increasing scrutiny in view of the safety risks associated with high pressure piping, pressure vessels, high temperature steam, hot fuel distribution systems, and burner installations. The long start-up and shut-down times for such systems can also present safety issues.

Increasing production efficiency

The increasing value of the secondary steel product and the need to increase plant efficiency to maximise revenues means that more frequent batch cycles are being required, with correspondingly less time allowable for maintenance and unplanned outages. In contrast, tighter control of licensing and insurance for boiler installations can all place added cost burdens and operational restrictions on the availability of process steam to run steam ejector vacuum systems. Under these circumstances the provision of instantaneous “vacuum on demand” at the push of a button becomes highly desirable.

To satisfy all these needs, integrated VD and VOD ladle tank vacuum stations combining low leak rates with high capacity dry mechanical vacuum pump modules, are now available. These enable a fully integrated and optimised approach to vacuum degassing, precisely specified for the actual metallurgical needs of the process, and completely free from any requirement to consume steam as a utility.

1. 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 [3]. 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 somewhat above this pressure since the degassing process is also influenced by many other factors, including argon stirring rate and duration.

In all cases where mechanical vacuum pumps are to be used it is an obvious requirement to install a suitable cyclone/bag filter unit between the ladle tank and the vacuum pumps, to protect the pumps from an excessive dust burden. 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 20 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:

- metallurgical hydrogen
- metallurgical nitrogen
- carbon monoxide (reaction of metallurgical carbon and metallurgical oxygen)
- argon (injected for stirring)
- air (from leakages into the system)

The masses of each metallurgical gas evolved during the process can then be used to derive a mass flow rate for each, and then a volume flow rate for each at the nominal end vacuum level of 0.67 mbar (hPa). The argon stirring rate is similarly converted into a volume flow rate at end vacuum level, as is the air leak. The sum of the flow rates can then be used to define the nominal pumping capacity required. It has previously been noted by the authors [4,5,6] that this calculation produces an interesting relationship. With typical operational parameters, 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. This equates to a mass flow equivalent of around 1.0 kg/h (air at 20^{o}C) per tonne at that pressure. Recent results with mechanical vacuum pumps on large systems (100 tonne heat mass and more) confirm this relationship and demonstrate that excellent metallurgical quality can be achieved, with residual hydrogen results down to 0.5 ppm H. This compares very favourably with typical steam ejector installations, which traditionally specify higher requirements for up to 2.4 kg/h (air at 20^{o}C) per tonne at 0.67 mbar (hPa).

2. ENERGY AND COST SAVINGS

A key feature of the modular 3-stage mechanical vacuum pump system is the potential for significant operational cost savings compared to the use of conventional steam ejector vacuum systems, and these savings arise from two key considerations.

The first is simply the operating cost comparison. The cost of raising steam to power the ejectors has now become the predominant factor in the operation of many VD plants. The underlying trend in fuel cost continues to escalate and the reliability of fuel supply is also becoming a serious issue in some regions of the world. On a typical VD plant, the cost of the steam consumed may account for over 50% of the total pumping system running costs, to which are then added the costs of feed water, condenser water, and the waste water disposal charges. Compared to the cost of steam, the electricity costs for running an equivalent mechanical vacuum pump system can be as little as 5% of the steam generation cost.

Secondly, there is the question of required pumping capacity. A typical specification for a new and highly efficient steam ejector system for a 135 tonne ladle tank degasser may provide for a pumping capacity of 330 kg/h (air, 20^{o}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. A typical steam ejector design capacity allows around 2.4 kg/h pumping capacity per tonne of steel. This appears to include a historical capacity excess, to allow for variation in steam quality and for routine degradation of the ejector performance due to fouling with process dust deposition between ejector cleaning operations.

In contrast, the true metallurgical off-gas, argon purge gas and air leakage flow rates from the process would imply an actual suction capacity requirement of around 1.0 kg/h per tonne, as previously noted. This figure is certainly borne out in recent experience with modular dry mechanical pump systems and implies that ejector systems are not only typically more costly to operate in energy terms, but also appear to be frequently oversized for the duty.

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 increased net operating cost, in comparison with modular dry mechanical pump systems. A typical operating cost comparison is shown in Figure 1, which illustrates potential annual operating cost savings of over 85% when dry pump modules are used.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	**Melt mass (tonnes)**	100		**OPERATING COST COMPARISON**									
2	**Annual tonnage**	250,000		**DRY MECHANICAL VACUUM PUMPS**				Data from standard assumptions					
3	**Cycle time in vacuum (mins)**	20		**vs.**				ENTER PARAMETERS IN YELLOW BOXES					
4	**Boiler output (kg/h)**	12500		**STEAM EJECTORS**									
5	**Process (defines dust kg/t)**	VD				Tappings per year		2500		Number of SSDMs		4	
7	**Cost criterion**		**Condition**	**Specific cost**		**Steam Ejectors**				**Dry running pumps including filter operating costs**			
9	**Consumption**												
10	- steam		12 bar, 194°C	18.00	€/tsteam	41.7	kg(st)/t	0.7500000	€/t				
11	- contact water		3 bar, 32 °C	0.10	€/m^3	3.3	m^3/t est.	0.3333333	€/t				
12	- non-contact cooling water		4 bar, 32 °C	0.08	€/m^3					0.0680000	m^3/t	0.0054400	€/t
13	- compressed air		5 bar	0.02	€/m^3					0.0001600	m^3/t	0.0000032	€/t
14	- nitrogen		5 bar	0.10	€/m^3					0.0352000	m^3/t	0.0035200	€/t
15	- vacuum pump oil			35.00	€/litre					0.0007840	litre/t	0.0274400	€/t
16	- power(pumps+auxiliaries)			0.06	€/kWh	0.42	kWh/t	0.0250000	€/t	0.6000000	kWh/t	0.0360000	€/t
17	Subtotal consumption							1.1083333	€/t			0.0724032	€/t
18	**Maintenance**	**€ per hour**	**man hours**										
19	- water pump service	30.00	4	120.00	€/pump	2500	tappings	0.0019200	€/t				
20	- SSDM service	30.00	20	600.00	€/SSDM					2500	tappings	0.0096000	€/t
21	- steam ejector cleaning	50.00	32	1600.00	€/job	400	tappings	0.0400000	€/t				
22	- heat exchanger cleaning	30.00	12	360.00	€/job					2500	tappings	0.0000006	€/t
23	- filter bag changing	30.00	16	480.00	€/job					800	tappings	0.0060000	€/t
24	- dust disposal			1.00	€/t					0.20	kg/t	0.0002000	€/t
25	- contact water disposal			1.00	€/m^3	0.33	m^3/t	0.3333333	€/t				
26	Subtotal maintenance							0.3752533	€/t			0.0158006	€/t
27													
28	**Spares**	**€ each**	**number**	**€/change**	**No. Changes**								
29	- filter bags	15.00	216	3240.00	3.125					0.0000125	sets/ton	0.0405000	€/t
30	- seals/bearings (water pumps)	700.00	per installed pump average per year.			4	pumps	0.0112000	€/t				
31	- seals/bearings (SSDM)	3500.00	per SSDM average per year.							4	SSDMs	0.0560000	€/t
32	Subtotal spares							0.0112000	€/t			0.0965000	€/t
33													
34	**TOTAL**							1.4947867	€/t			0.1847038	€/t
35	Difference							0.0000000	€/t			1.3100829	€/t
36	Annual saving									Saving		328	k€
37													

Fig. 1. Typical operating cost comparison spreadsheet for dry mechanical vacuum pump modules compared to steam ejectors for a nominal 100 tonne VD process

3. EMISSIONS REDUCTION

In line with the objectives of the UNFCCC and its 1997 Kyoto Protocol, much national and regional legislation now imposes monitoring and control regimes on GHG emissions. As CO_2 is the predominant GHG, the Protocol also provides for carbon emissions trading schemes, for example such as the European Union Emissions Trading Scheme (EU ETS), established by the European Commission Directive 2003/87/EC.

Overall, the global iron and steel industry is a significant contributor to the global inventory of GHG emissions. According to the Intergovernmental Panel on Climate Change (IPCC), iron and steel making contributes around 1500–1600 Mt of CO_2 per year, or around 6 – 7% of the total global anthropogenic (man-made) CO_2 emissions. In some countries the level of steel industry GHG emissions accounts for a very significant proportion of the national inventory. Average CO_2 emissions per tonne of steel manufactured vary from 1.25 tCO_2/tonne in Brazil up to 3.8 tCO_2/tonne in China [7]. Apart from general plant efficiency, this value is strongly influenced by the proportion of production which uses recycled scrap and EAF processing, (more efficient in terms of energy usage and hence has reduced fossil fuel consumption).

Many national and international steel industry associations are making commitments to significant reductions in GHG emissions. One of the more significant recent initiatives, announced by the World Steel Association, is the commitment to collect and report CO_2 emissions data by steel plants in all of the major steel producing countries around the world [8]. Although secondary steel vacuum degassing is small scale compared to bulk steel production, a significant proportion of VD plants still utilise steam-powered ejectors to generate the required vacuum, and the generation of this steam can represent a significant environmental burden to the plant, as well as an economic liability.

Therefore it is clearly an environmental advantage to completely eliminate the use of steam here, and this can now be done very practically by using modular dry mechanical vacuum pump systems in place of the traditional steam boiler and ejector array.

4. MODULAR DRY MECHANICAL VACUUM PUMPING SYSTEM

The configuration of the simplest vacuum pumping system to attain a VD tank pressure below 1 mbar (hPa) and provide adequate suction capacity is a 3 stage configuration, and initial exploitation of early customised vacuum pumping systems (both 3 and 4 stage types), has also been reviewed by the authors [4,5,6]. Such customised systems may be designed to provide a very specific performance for an individual plant, but customisation results in an inflexible, inefficient, and generally more complex and costly approach, compared to the use of the more recent modular 3 stage vacuum pumping systems which have been developed.

The suitability of the standardised modular pumping system, with design and performance optimised for the steel degassing processes, has now been well established. The modular approach minimises power consumption, reduces utility consumption, and enables quick and easy installation, and commissioning. This approach has resulted in the development of the latest steel degassing pump module, which is a fully integrated, three stage pump system on a transportable skid, optimised for the VD and VOD processes.

The pump selected for stage 1 of the modular degassing system is a 36,000 m^3/h nominal displacement vacuum booster, characterised as a heavy duty vacuum machine with high efficiency, requiring only a 30kW 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 stage 3 (primary) pumps, the booster provides a peak volumetric efficiency of around 80% and a typical net pumping speed of 28,300 m^3/h at around 0.67 mbar (hPa), as indicated in Figure 2. The unit selected for stage 2 of the modular degassing system is a vacuum booster with a nominal displacement of 8,640 m^3/h and capability to provide a high compression ratio at intermediate vacuum levels. This is usually fitted with a 55kW motor. This pump also provides a volumetric efficiency of up to 80%, depending on configuration, and is also configured with the required safety purge facilities.

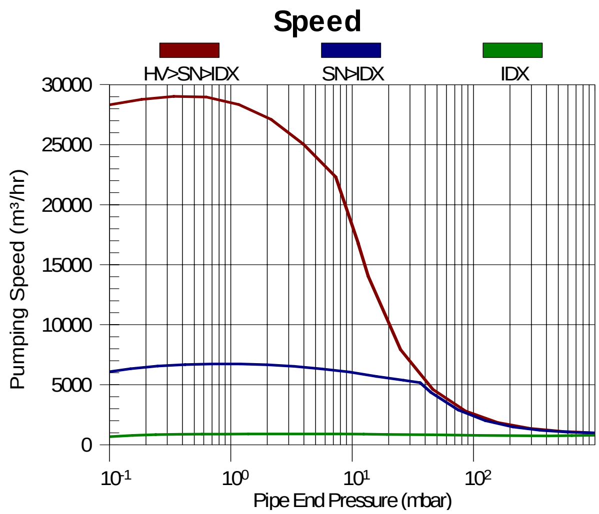

Fig. 2. The speed curves of each stage of the optimised 3 stage vacuum pumping module

The dry running “primary” vacuum pump of the system, the pump which finally exhausts the pumped gases to atmospheric pressure, has a very high compression capability and is also very robust with an excellent resistance to dust wear. This is the latest generation of “IDX” large, high efficiency, double-ended, variable pitch screw pumps, which has now become an international standard in dry vacuum degassing. This pump also uses a 30kW motor and provides a relatively flat “backing” speed curve of nominally 1000 m^3/h (or optionally 1300 m^3/h) behind the stage 2 booster.

The resulting steel degassing module is illustrated in Figure 3. 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

Fig. 3. Three stage, dry mechanical vacuum pump module for steel degassing

which only needs to be mounted in place and connected to the process inlet manifold, exhaust manifold and utilities, this modular concept also gives the major advantage of complete flexibility. This is because any suitable number of modules can be installed in parallel to provide a specific pumping capacity for current degassing system requirements. Then if heat sizes are to be increased, more pumping capacity can easily be added later, without disturbing the existing operations, by mounting additional modules in parallel to the installed modules. Alternatively, modules can simply be removed and re-located to other degassing installations as plant requirements change.

Compared to early, customised mechanical vacuum pumping systems, the introduction of the modular concept, 3 stage, dry pump solution brings five other key advantages. These are:

a. Lower electrical power consumption
Each pump in the module has a standard vacuum duty size motor, run from a suitable electronic variable frequency drive, which gives maximum electrical efficiency throughout the whole operating cycle, and minimises overall power consumption. In comparison, other systems using exhauster type vacuum pumps with internal gas recycling and large, fixed speed motors, consume large quantities of power, and give lower operating efficiencies.

b. Lower utilities consumption
Each pump in the standard dry pump module consumes only a small quantity of pump cooling water, as the design is optimised for the pumps to run appropriately warm. Each pump similarly consumes only a small flow of nitrogen purging gas. In contrast, other customised systems using cold running pumps with large interstage gas coolers can consume significantly higher quantities of cooling water. The water consumption can be even higher where exhauster type pumps fitted with large heat exchangers are used.

c. Lower space requirements
The dry pump module is designed to occupy the minimum space in order to give the most compact installation, while maintaining full accessibility for service and maintenance. Older style customised systems typically require more space for the installation.

d. Lower installation costs
Each standard module is supplied fully piped, wired and tested, and the module is simply removed from the delivery truck and installed on a suitable pump room floor. This significantly shortens both time and costs for the required installation and commissioning, compared to a customised system. Customised systems have to be assembled in place, and also typically require more complicated manifolding and valve arrangements, which add to the cost, complexity and installation time of the system.

e. Lower operating costs
As noted previously, the overall operating costs of a dry modular pumping system are very substantially reduced compared to the costs of a running steam ejector vacuum system. Furthermore, compared to customised mechanical pumping systems, modular dry systems offer further cost savings, as the power and utilities consumptions are lower, and the reduced numbers of manifolds and valves in the modular systems also mean lower overall costs for maintenance and cleaning. Compared to early, customised 4 stage mechanical systems using high power, water-cooled exhauster pumps, a typical dry modular system can offer additional operating cost savings of over 60%, due to their substantially lower demand for electrical power and cooling water.

5. SYSTEM SIZING AND CONTROL

Based on proven experience and the foregoing considerations, 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 1. In degassing plant where leakages rates are maintained to sensible levels, the suction capacity requirement of around 1.0 kg/h per tonne at 0.67 mbar (hPa), as previously noted, is demonstrated to yield good degassing results.

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Table 1. Typical relationships between parameters for modern ladle tank vacuum degassers (VD process) and suitable numbers of standard vacuum degassing modules

typical VD heats used tonnes	no. of standard modules	mass flow kg/h @ 0.67mbar	pump speed m3/h @ 0.67 mbar	typical total system volumes total m3
20 - 25	1	22.6	28,300	60
30 - 50	2	45.2	56,600	113
60 - 80	3	67.8	84,900	170
90 - 100	4	90.4	113,200	245
110 - 130	5	113	141,500	300
140 - 150	6	135.6	169,800	335
160 - 180	7	158.2	198,100	400
190 - 200	8	180.8	226,400	460
210 – 220	9	203.4	254,700	510
230 - 240	10	226	283,000	550

Overall controllability of the applied pumping speed is an important issue, and the use of electronic variable frequency drives to control all of the pump motors produces significant benefits in control. As well as providing maximum pumping efficiency, optimising energy use, and allowing the pump down to proceed in the most effective way, variable frequency drives allow the plant control system to directly control the booster pump speed. This means the control system can rapidly change the overall pumping rate when demanded by the operator, for example in response to any incidence of slag foaming in the tank.

6. SURVEY OF RECENTLY OPERATING PLANTS

Table 2 below provides a summary of some recent modular mechanical vacuum pumping installations on steel degassers. A typical pumping system installed on a 90 tonne VD process is illustrated in Figure 4.

Table 2. Recent operating modular mechanical vacuum pump systems for vacuum degassing

Year commissioned	Country	Heat size (tonne)	Peak suction capacity (m^3/h)	Number of pump modules
2006	USA	41	84,900	3
2006	Spain	42	35,000	2
2006	Ukraine	100	141,500	5
2007	Turkey	90	113,200	4
2007	Ukraine	60	84,900	3
2008	Italy	100	84,900	3
2008	Romania	100	113,200	4
2008	Italy	40	56,600	2
2009	Brazil	30	56,600	2
2009	Germany	60	84,900	3
2009	South Africa	20	28,300	1
2009	USA	25	56,600	2

7. **SUMMARY**

Modern VD ladle tank installations with low leak rates, together with modular dry mechanical vacuum pump systems, now enable a highly integrated and fully optimised degassing station to be installed to meet the actual metallurgical needs of the process. The modularity of the design also allows complete expandability and effective "future-proofing" of the installation. This approach is not only ideal for compact EAF installations but also suitable for larger degassing plants, remaining economic for installations for up to 250 tonnes heat mass, or more.

Fig. 4. Typical modular dry mechanical vacuum installation for 90 tonnes VD

The major benefits of such systems include operating energy savings of up to 90% or more compared to steam ejector systems, and a variety of environmental benefits. These arise via the elimination of legacy boiler systems and therefore provide an instant reduction in plant CO_2 GHG emissions, a reduction in water consumption, and elimination of contaminated waste water disposal from the steam ejectors.

The modular dry pump approach also provides excellent operational flexibility, maximises efficiency while minimising costs, and enables the integration of pump control directly into the plant control system to provide a true push-button, "vacuum on demand" plant. The excellent controllability is especially beneficial in dealing with slag foaming, and enables consistent performance and proven, high quality metallurgical results. Field experience also shows rapid commissioning and start-ups are achievable, and the rapidly-growing numbers of operating steel degassing plants around the world using such modular dry vacuum pumping systems demonstrates the effectiveness of this technology.

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