Advantageous optimisation of the vacuum oxygen decarburisation (VOD) process with mechanical vacuum pumps

High costs for vacuum generation and maintenance can be overcome by replacing steam ejector pumps with mechanical vacuum pumps for VOD (and VD) processes. Initial concerns about technical applicability of mechanical pumps for vacuum processing of large heats have proven unfounded – there is no technical upper weight limit. With detailed knowledge about the vacuum process, mechanical vacuum pumps can be successfully engineered for any heat weight where a steam ejector pump would previously have been selected. The suction speed of mechanical vacuum pumps can be ideally controlled to fit the various phases of vacuum processing.

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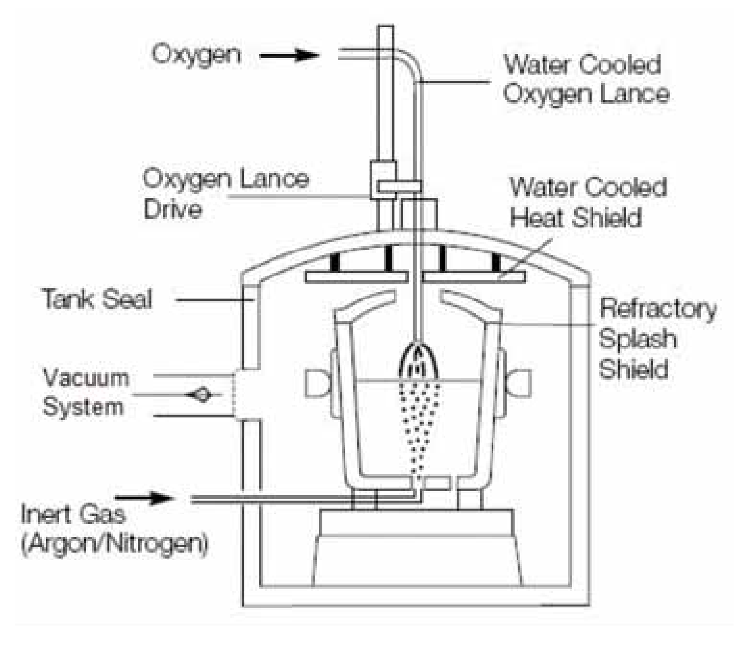


Fig 1 **VOD unit**

PROCESS OVERVIEW

Secondary refining equipment for stainless steel includes the AOD convertor and the VOD unit. Stainless steel contains a large amount of chromium and, since Cr is a strong oxide former, during normal refining it is difficult to decarburise stainless steel to a sufficiently low carbon level while preventing chromium oxidation. Low carbon levels are, therefore, achieved by decreasing the partial pressure of carbon monoxide in the refining atmosphere to ensure preferential decarburisation in the presence of chromium. In practice, this is done in the AOD by dilution using argon and in the VOD by reducing the pressure in the unit.

The major attributes of the VOD process are low argon consumption, the ability to produce very low N and C steels, excellent Cr recovery and good compositional control. A schematic of a typical plant is shown in *Figure 1*.

DECARBURISATION

Decarburisation of stainless steels under vacuum comprises two steps:

- Programmed oxygen blow under partial vacuum by direct oxidation with O_2
- Final decarburisation (boiling off) under deep vacuum by use of dissolved oxygen in the melt

Some aspects of the process will now be described in more detail.

Programmed oxygen blow In converter steelmaking, the concept of a programmed oxygen blow in combination with a specifically engineered number and type of oxygen lance nozzles is common practice. This helps optimise slag formation and minimises splashes by controlled variation of oxygen flow and lance-to-bath distance in the course of blowing.

The concept of a programmed oxygen blow has been adapted to the VOD process in a slightly different form. Since the slag is solid for a considerable part of the vacuum process and dephosphorisation cannot be applied, the key points are:

- High rate of main decarburisation while minimising splashes
- Maintaining a defined oxygen jet penetration into the liquid metal
- Minimising metal over-oxidation and over-temperature by reducing vacuum vessel pressure and oxygen flow towards end-of-blow

Boiling-off Oxygen blowing is carried out only to the point where dissolved oxygen can be used to perform the final decarburisation. This phase, boiling-off, is typically from 0.03-0.05% C down to 0.01-0.02% C.

Slag reduction It is inevitable that Cr, together with some Mn and Fe, are oxidised during the oxygen blow. This causes the slag to become completely solid by saturation with Cr_2O_3, so in order to liquefy the slag and render it deoxidising and desulphurising, reducing agents (Al, FeSi) and slag builders (lime, bauxite, fluorspar) are added and made to react with the slag for 8-20 minutes under vigorous Ar stirring.

Decarburisation optimisation Decarburisation of stainless steel is usually optimised towards highest productivity. One of the first measures to undertake when engineering a new VOD installation is, therefore, to determine the upper decarburisation rate limit. Furthermore, since decarburisation by oxygen blowing ends at high temperature (over 1,700°C), the approach to end-of-blow must be well defined so as to minimise over-oxidation and over-temperature of the melt.

The rate of decarburisation in the VOD process is considerably lower than in a BOF. The explanation is simple: Decarburisation generates great turbulence and foaming in the steel and slag. A BOF will have a generously designed specific, inner volume of 0.55-0.60m^3/t of metal to contain them. In contrast, ladles used for the VOD process will typically have a specific volume of only 0.2-0.3m^3/t, including a freeboard of 1.1-1.2m. Available specific reaction volume therefore severely limits the rate of decarburisation as compared with a converter process. A BOF can reach a decarburisation rate of 0.10-0.13% per minute, using both bottom/side tuyeres and a top lance. *Figure 2* illustrates data from a number of processes.

Since it is largely the available reaction volume above the ▷

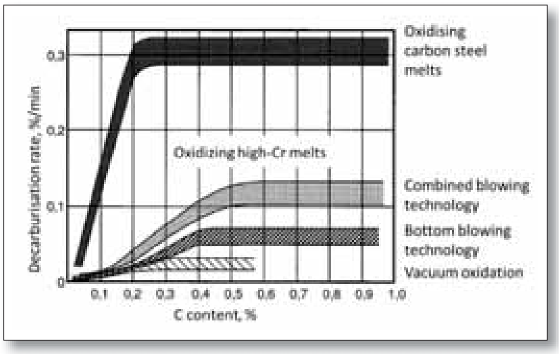


Fig 2 **Decarburisation rates in various processes (*from ref 2*) ('oxidising C steel melts' refers to BOF process)**

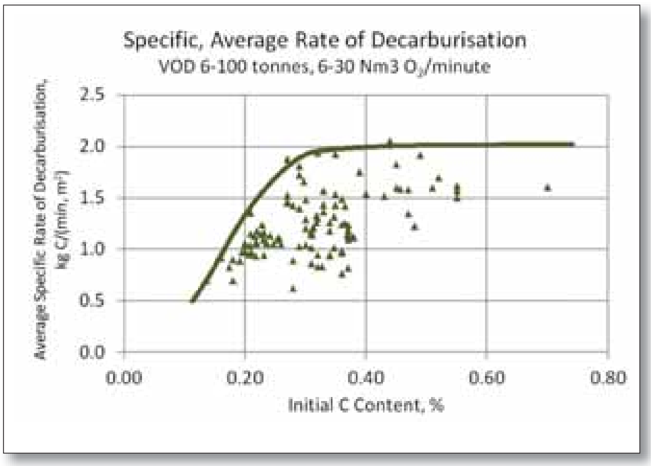


Fig 3 **Specific decarburisation rate in VOD (*from ref 2*)**

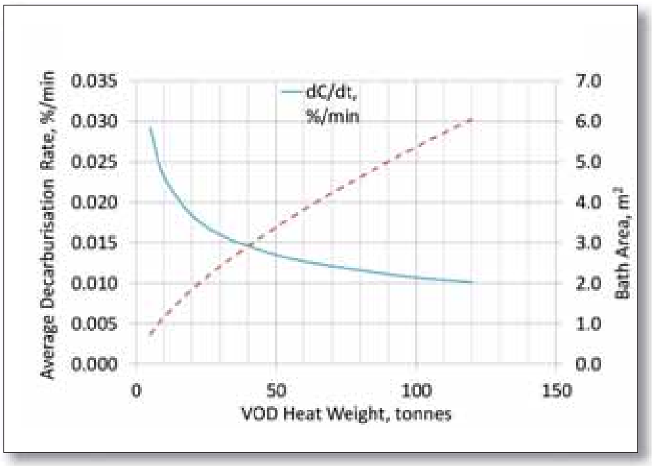


Fig 4 **Average decarburisation rates as function of steel weight (*from ref 2*)**

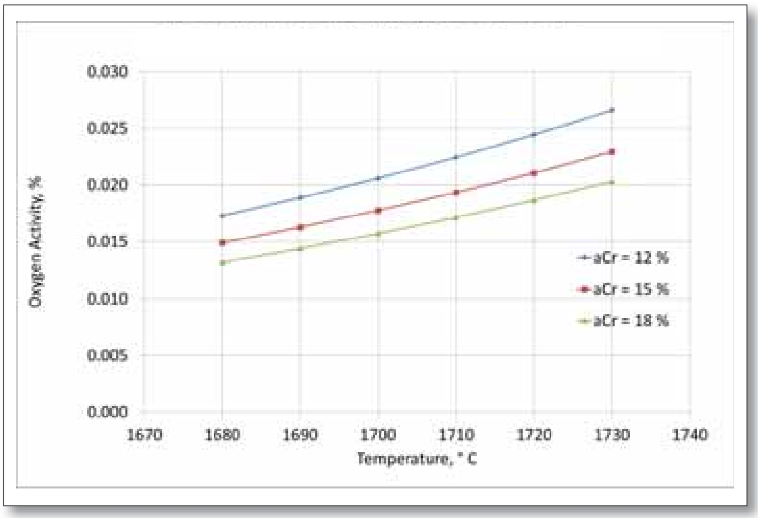


Fig 5 Oxygen activity as function of Cr activity and temperature (*from ref 2*)

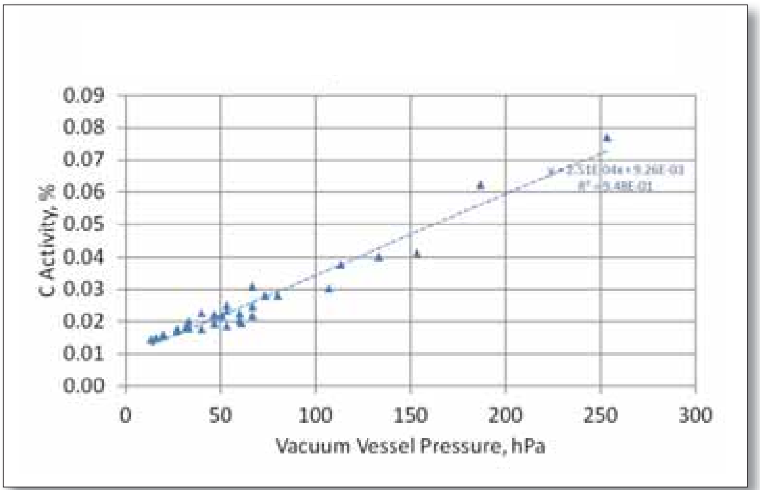


Fig 6 Carbon activity as a function of vacuum vessel pressure at end of blow, 1,660-1,700°C (data reprocessed from ref 1)

bath that determines maximum rate of decarburisation in the VOD, it makes sense to describe the maximum specific rate of decarburisation in terms of kg of removed C per m^2 bath area per minute.

A study of several VOD heats from 5 to 100t shows that the average rate of decarburisation is 2.0kg/(m^2.min) (*see Figure 3*).

The maximum, average specific rate of decarburisation is reached only above approximately 0.4% C. This follows from the fact that the graph shows the average rate and that, in any case, the rate slows down at C contents lower than 0.2-0.3% C for reasons elucidated below.

Converter processes can in actual fact decarburise 5-10 times faster than the VOD process, which clearly shows a limitation of the VOD. A converter can also easily decarburise from 2% C and 0.3% Si, which would be virtually impossible with suction speed control during the decarburisation phases in the VOD for reasons of refining time and slag formation.

As can be expected, there is no clear dependency of steel weight on the specific average decarburisation rate. As a consequence, the achievable average rate of decarburisation drops with increasing steel weight because the specific bath area drops with increasing steel weight.

For an assumed, 'ideal' bath height-to-diameter (H/D) ratio of = 1.0, the 2.0kg Ckg/(m^2.min) translates into *Figure 4*.

THERMODYNAMICS OF APPROACH TO END-OF-BLOW

Blowing oxygen onto a high chromium melt results in successive and overlapping oxidation of the constituent elements. The sequence in which the elements are oxidised depends on temperature, the instantaneous activity of each element and its oxide, and on the equilibrium constant for each of the elements.

Towards end-of-blow at a C content of 0.03-0.05% the oxygen activity will typically have risen from an initial level of 10-30ppm to 200-250ppm (see *Figure 5*). The final oxygen activity is controlled by Cr because this is the only remaining element that is still relatively close to its high starting analysis. It is this oxygen activity in conjunction with vacuum vessel pressure and temperature that will determine the C content at end-of-blow.

The point at which Cr finally takes overall command of the oxygen activity is called the critical C content, which is not a fixed analysis but is in a range of typically 0.14-0.18% C. From this point onwards the rate of decarburisation is no longer directly proportional to the oxygen flow, but a function of temperature rise and CO partial pressure.

The higher the Cr activity, the more the temperature has to be raised to reach a certain oxygen activity. However, what is really of interest is the behaviour of C. It is obviously subordinated to the oxygen activity determined by Cr towards end-of-blow. The equilibrium between C and O is pressure-dependent according to:

$\underline{C} + \underline{O} \longleftrightarrow CO$ ....(1)

Deriving from oxygen activity, equilibrium constants and expected C activity, the relationship between C activity, temperature, CO pressure, Cr activity and Cr_2O_3 activity can be formulated as follows:

$a_{\underline{C}} = ((p_{CO}{}^{3} * a_{Cr}{}^{2})/(a_{Cr2o3} * f(T)))^{1/3}$ ....(2)

In (2), only CO pressure and temperature are available for optimisation because the Cr activity is given by the steel grade.

Theoretically, C activity at end-of-blow can be predicted as expressed in (2). In reality, however, the situation is slightly more complicated because the calculated CO pressure is not quite equal to the vacuum vessel pressure (empirical data shows that the individual system has its own C-removal characteristics) and the bulk C content in the melt is higher than at the melt surface in contact with the vessel pressure.

Allowing for some empirical plant-specific corrections of the CO pressure in equation (2), there is a surprisingly good constancy in the relation between C activity and measured vacuum vessel pressure within a defined temperature range, as shown in *Figure 6*. Carbon is described here in terms of activity in order to take into account interaction by Cr and other elements.

The graph shows that the C activity will drop by approximately 0.0025% for every 10hPa drop in end-of-blow vacuum vessel pressure.

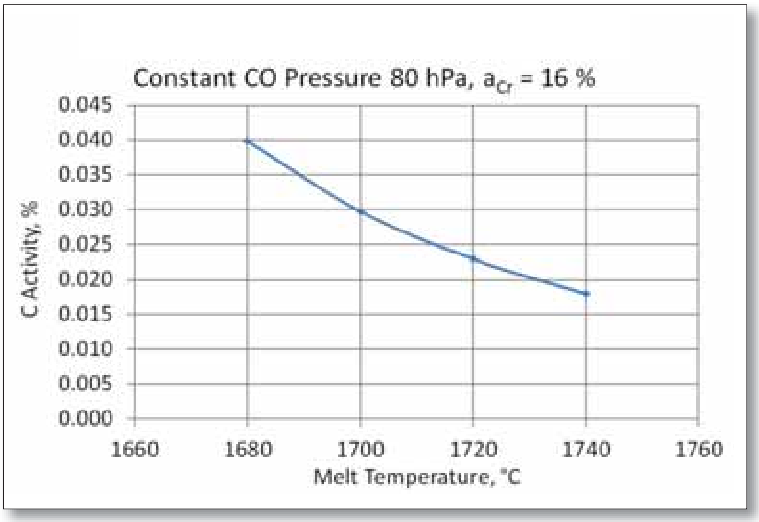
These numbers are not generally applicable, but give an idea of what can be achieved in a given melt shop with a well-controlled VOD process, even without off-gas analysis.

Assuming that temperature and vacuum vessel pressure can be controlled independently, the influence of temperature on C activity at constant vacuum vessel pressure is as shown in *Figure 7*.

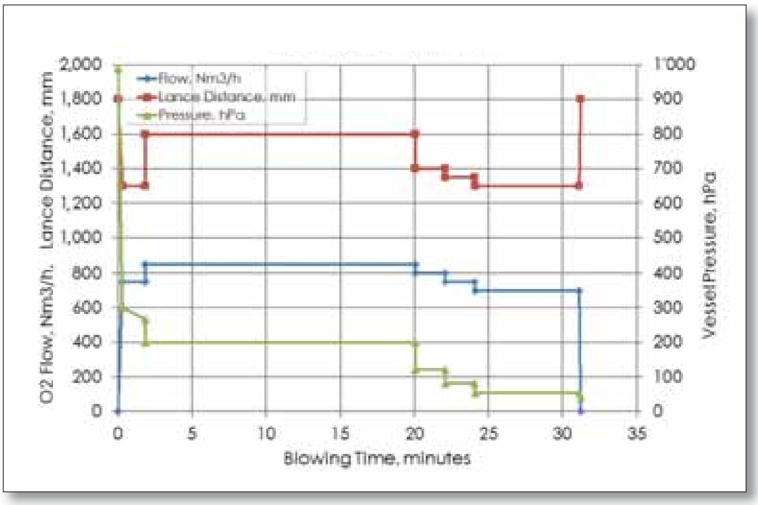
An increase of end-of-blow temperature by 10K reduces the C activity by 0.0025-0.0050%, again specific to a given melt shop and well-controlled VOD process.

BLOWING PROGRAM

Modern VOD practice includes the use of a blowing programme, calculated in real time for each heat. It typically divides the oxygen blow into five phases, each with its optimum oxygen flow, vacuum vessel pressure and lance-to-bath distance. An example from a 50t heat of grade AISI 609 steel is shown in *Figure 8*. ▷



Ⓐ Fig **7 C activity as a function of temperature (*data reprocessed from ref 1*)**



Ⓐ Fig **8 Blowing programme example**

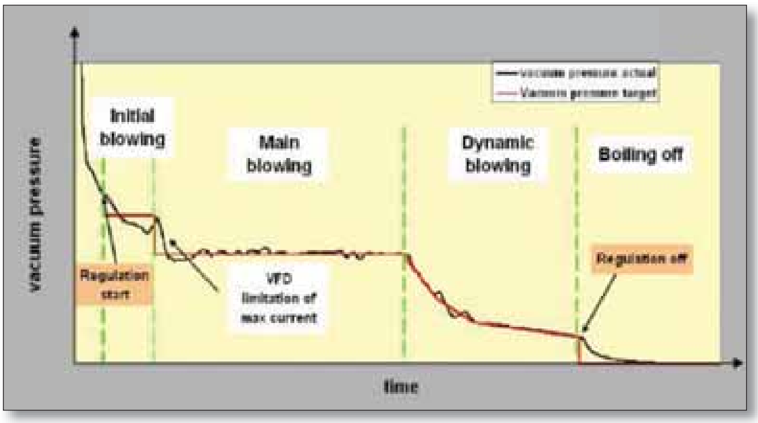


Fig 9 Vacuum pressure control during VOD process (*from ref 4*)

Blowing starts with the lance near to the bath to ensure ignition. After a few minutes, decarburisation begins and the lance distance is increased to protect the oxygen lance and to reduce spitting.

The oxygen blow now proceeds at full speed until the critical C content approaches. From the critical C content onwards, oxygen will increasingly react with Cr, which is an energy-rich fuel. If the oxygen blow were to proceed with constant flow, the temperature would from then on rise faster than previously. This is not desirable and therefore the oxygen flow is reduced, continuously or stepwise, so that temperature continues to rise only slowly. In order to maintain oxygen jet penetration into the metal bath, the lance distance is reduced commensurate with reduction in oxygen flow.

Decarburisation is now mainly promoted by falling vacuum vessel pressure as formulated in equation (2) and shown in *Figures 8 and 9*. It continues until the desired end-of-blow C content has been reached. The mechanical vacuum pump is excellently suited to control the vessel pressure required for optimum decarburisation.

BOILING-OFF

The C content at end-of-blow is still considerably higher than the final aim C content. Carbon is therefore removed by reaction with dissolved oxygen in combination with strong Ar stirring during the boiling-off phase. This auto-decarburisation is provoked by reduction of vacuum vessel pressure according to the pressure-dependent reaction, equation (1).

The rate of auto-decarburisation depends on the rate of carbon and oxygen transport to the vicinity of the melt surface where the reaction takes place. In a given ladle, this transport rate is mainly dependent on Ar flow rate. The decarburisation rate during boiling off is generally described by an exponential function of the type:

$$\%C = (\%C_{init} - \%C_{infinit}) * e^{-k*A/V*t} + \%C_{infinit} \quad \text{...........................(3)}$$

Where:

C_{init} is initial C

$C_{infinit}$ is C content after infinite time

k = decarburisation rate constant, m/min

A = stagnant bath area, m^2

V = bath volume, m^3

t = reaction time, minutes

It is possible to reach a low C content at low oxygen activity, but it requires low CO pressure and low temperature at end-of-blow, as understood from C activity. It is also possible to reach the same C content at higher oxygen activity, but with higher temperature and CO pressure.

Experience shows that a decarburisation rate constant of about 0.20m/min can be achieved on the condition that the O/C molar ratio is sufficiently high. If there is not sufficient dissolved oxygen present, oxygen must come from oxides in the solid ladle slag, which considerably slows down decarburisation. The temperature pressure window at end-of-blow must therefore be optimised so as to fit requirements on final decarburisation during boiling off.

The vacuum vessel pressure must be sufficiently low so that it initiates the auto-decarburisation reaction, however working with an excessively low pressure will not really speed up decarburisation, merely create more slopping. The vacuum vessel pressure should therefore be lowered gradually, to allow sufficient control over boiling reactions. Again, the mechanical vacuum pump is the preferred tool, with its great flexibility in controlling suction speed, and hence suction pressure, as required by the process.

SUCTION SPEED CONTROL DURING DECARBURISATION PHASES

Control principles Vacuum pump suction speed control is the key to process control, both in terms of achieving the metallurgical aim and in limiting slopping. Since generation of off-gas and vacuum pressure requirements vary drastically in the course of a complete treatment, the vacuum pump

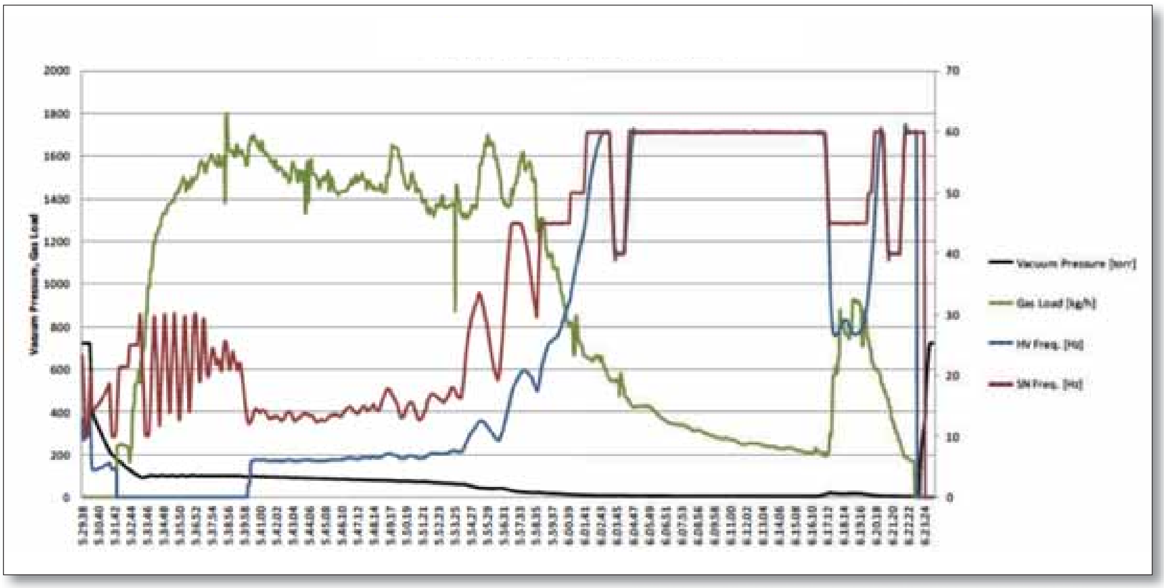


Fig 10 VOD process parameter trends (*from ref 4*) (HV= 1 Stage booster, SN = 2nd stage booster)

must be very flexible. As a general principle, the suction speed (flow through the pump) is controlled by varying motor frequency and/or switching electric motors on/off and/or opening or closing shut-off valves in the vacuum pump. No electric energy is wasted for suction speed control. In comparison, variation of suction speed with a steam ejector pump is mostly effected by variable recirculating off-gas, which varies the suction speed, but does not reduce the steam consumption when reducing suction speed.

Vacuum pump control during oxygen blow phases

In the first few minutes of the oxygen blow, oxygen is consumed mainly by Al and/or Si. Consequently, the off-gas flow is very low. When these elements have been oxidised, the oxygen activity in the steel bath increases, and decarburisation begins and generates CO and CO_2. In order to avoid excessive slopping due to eruptive boiling when decarburisation starts, it is necessary to keep the vessel pressure artificially high for a few minutes as shown in *Figures 7 and 8*. The vacuum pump suction speed is therefore controlled so that the pressure stays relatively constant at 150-200hPa during oxidation of Al and/or Si.

During decarburisation the pressure is kept lower and falling towards end-of-blow. There are two suction speed control possibilities:

- The tank pressure is controlled directly to successively lower levels by acting in closed-loop on electric motor frequencies. An example is shown in *Figure 8*.
- The tank pressure is controlled indirectly by setting fixed electric motor frequencies that let the pressure vary and finally drops as a consequence of successively falling off-gas flow, much like the way water ring pumps work, but enabling variation of frequencies.

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Fig 11 Arrangement of parallel vacuum modules in the pump room of Mechel VOD-plant in Russia (*from ref 4*)

	Costs/ unit	**Steam ejectors**	**Ejectors Liquid Ring Pump**	**Dry pumps and dust trapping**
Utilities	**€**	**€**	**€**	**€**
steam	20.0/t	1.40/t	1.10/t	
condenser/seal water	0.04/m^3	0.17/t	0.17/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			0.001/t
gear oil	3/litre			0.02/t
electricity	0.05/kWh	0.03/t	0.08/t	0.27/t
Maintenance				
nozzle cleaning	800/outage	0.1/t	0.1/t	
heat exchanger cleaning	240/service			0.05/t
filter cleaning	320/service			0.03/t
dust disposal	100/t	0.01/t	0.01/t	0.1/t
sludge disposal	1.8/m^3	0.4/t	0.4/t	
Spares				
filter bags	1,200/set			0.12/t
Operating cost/ t €		2.11/t (delete)	1.86/t (delete)	0.594/t (delete)
Total operating cost €		527,500	465,000	148,500
Annual saving with dry pumps €		**379,000**	**316,500**	

Table 1 Operating cost comparison for VD *from ref 5*. (*Note: there is no published cost saving data available for VOD but as VD is quite similar to VOD, the conclusions are the same*)

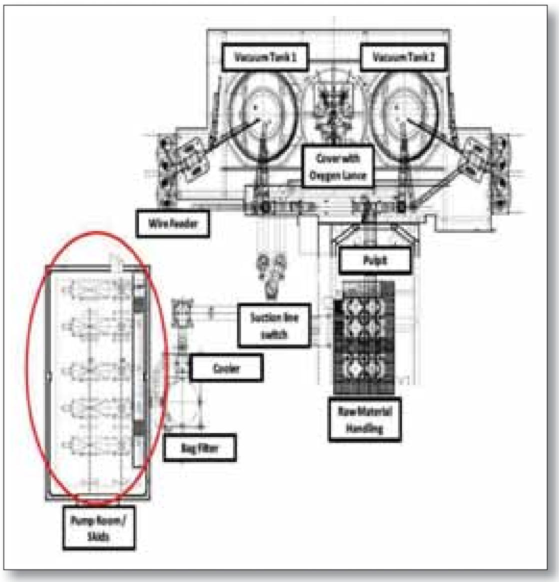

Fig 12 Layout of Mechel VD/VOD station (*from ref 4*)

The mechanical vacuum pump lends itself very well to both control principles. The process engineer will select the most convenient method.

Vacuum pump control during boiling-off During boiling-off, a considerable amount of carbon is removed very quickly at falling pressure. These are critical conditions that invite heavy slopping and operational problems unless the pressure descent is gradual and well controlled. It is difficult to achieve this with a steam ejector pump. With a mechanical pump, it is easy to control suction speed and it is also easy to automate the boiling-off process. As the rate of auto-decarburisation is known – as expressed in equation (3), just as in during the oxygen blow, the vacuum pump enables automatic control in one of two ways:

- The tank pressure is made to fall over time along a pre-programmed curve, directly controlled by constant frequencies of the mechanical pumps' electrical motors
- The suction speed increases over time along a pre-programmed curve, which indirectly reduces the tank pressure.

Figure 10 shows the main trends of a VOD process lasting about one hour, applying pressure regulation by changing the frequency of the pumps.

PROPERTIES OF A MECHANICAL VACUUM SYSTEM

The high dust load during VOD processing requires a suitable filter system to protect the mechanical components. There are steel industry-standard bag filters available in the market and an additional upstream off-gas cooler protects filter bags as well as the mechanical vacuum system from the high heat load caused by the high-pressure range.

The layout of the mechanical vacuum system as well as the right pump sizing reduces the number of interfaces to an optimum, ensuring easy integration into process control and thus enabling stable operation under any process condition. Mechanical vacuum systems with equal or similar suction speed performance may comprise a different number of vacuum pumps as a result of the selected pump size and/or number of vacuum stages. Most common are three- and four-stage systems, comprising backing pumps in the first stage and roots pumps in the further stages. The number of stages is determined by two parameters:

- The suction speed performance of the backing pumps, ensuring short pump down times and stable rough vacuum operation.
- The compression ratio associated with the selected Roots pumps, enabling high performance down to a process pressure of 0.67mbar. The excellent compression ratio of the Roots pumps will minimise the number of stages – and thus pumps – and will, in addition, drive the vacuum system to an economic and environmental friendly solution. Roots pumps consume less power and cooling water, hence also help to lower investment cost compared to backing pumps.

The selection of vacuum pump size should be determined by the minimum required number of pumps to ensure uptime in the unlikely event of pump failure in any of the stages, whilst also aiming to maximum pump size. In practice, it has been shown that a loss in suction speed of <30% will maintain the process operation with slight restrictions in final pressure and process time, without compromising steel quality. For a steel plant with short cycle times and high productivity, additional installation of redundant pumps might be applicable, depending on the size of the vacuum system. This will, at the same time, buffer unscheduled leakages in the system.

For smaller heat sizes the use of smaller pumps might be applicable, whereas up-scaling is limited by physics. For instance, enlarging the pump chamber to increase the suction speed will lead to larger masses, encountering several limitations: in handling due to weight, in economics due to higher investment costs, and in a lower compression ratio due to longer clearance lines. At the same time, the higher inertias of larger masses leads to slow acceleration of the rotational speed, so worsening the controllability of the process pressure.

Alternatively, the suction speed of a vacuum pump can be increased by higher frequencies and consequently smaller mass of the rotors. Despite the installed filter upstream of the vacuum system, a considerable amount of dust still passes through the vacuum system, building up dust deposits on the rotors. In conjunction with the high operation pressure and the cyclic operation, this adds further stress to the pumps, which increases with higher rotational speed and smaller rotor masses.

A simple layout without additional lines, valves and instruments will reduce interfaces to a minimum and guarantee a stable process control.

In practice, a three-stage system in conjunction with an intermediate heat exchanger, dissipating the compression heat of the powerful second stage in conjunction with a parallel design, has been shown to be an effective design. An example is shown in *Figures 11 and 12*.

ADDITIONAL ADVANTAGES OF DRY PUMPS

Vacuum system tightness The VOD process generates a mixture of CO, CO_2, N_2, Ar, O_2 and H_2. In a traditional installation, this gas goes through the system, but is also in intimate contact with cooling and sealing water in condensers and water ring pumps. Since these gases, with the exception of Ar, dissolve in water, it means that the water coming from condensers and water ring pumps becomes contaminated. CO must therefore be removed from the water in a scrubber before the water comes into an open system.

In an installation equipped with a mechanical vacuum pump, there is no contact between process off-gas and cooling water. The system is completely dry and, except when idling, is closed up to the stack mouth. Contamination of water with process gases, therefore, does not occur.

Dust Since no water comes into contact with the process off-gas, the dust generated remains completely dry. It is separated and collected and can be disposed of manually or automatically, together with dust from the EAF and LF at a considerably lower cost than if it were disposed of as sludge with much greater volume.

Operating cost As proven in many installations, the mechanical vacuum system provides a huge cost advantage, ensuring swift return on investment. *Table 1* compares different pump systems.

CONCLUSIONS

- In modern VOD systems, mechanical vacuum systems can contribute significantly to the optimisation of the process.
- The use of automatic pressure regulation controlling the suction speed of the pumps can achieve high decarburisation rates along with short process times for the process.

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- Dry mechanical vacuum pumps offer significant advantages in operating cost and readiness for operation compared to traditional steam ejector systems. A well-dimensioned vacuum system will provide further advantages.
- In combination with a powerful automation system, it provides an economic and environmentally friendly solution for production of a wide variety of steel grades.
- This solution is proven in practice at several installations with high demands on steel quality and process times. **MS**

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REFERENCES

[1] Josef Otto, *The concentration movement of high chromium steels suring vacuum refining and process monitoring through continuous oxygen partial pressure of the exhaust gas*. Dissertation, Aachen, 1975

[2] *The Japan Society for the Promotion of Science, Steelmaking Data Sourcebook*, Gordon and Breach Science Publishers, pp95,1998

[3] Karl-Heinz Heinen: *Elektrostahlerzeugung*. VDEh, Verlag Stahleisen, Düsseldorf, p558, 1997

[4] Guiseppe Franco and Harald Koblenzer, 'Vacuum Tank Degassing Station with Dry Mechanical Pumps for VD and VOD Process at Kama Stal and Mechel Plants', in *Proceedings EEC*, p5, 2012

[5] Simon Bruce, Vic Cheetham and Graham Legge, 'Recent Experience of Mechanical Vacuum Pumps Replacing Steam Ejectors in VOD and VD Processes', Abstract, p25, in *Proceedings ASIA STEEL 2009*, Busan-Korea, 24-27 May 2009