The cost structure of vacuum steel degassing including ladle furnace treatment

Kostenstruktur der Vakuumentgasung unter Berücksichtigung der Pfannenofenbehandlung

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The cost for the conversion of steel in secondary steelmaking including a ladle furnace and various vacuum treatment processes have been investigated for a large heat range comparing two commonly used vacuum pump systems. Dry operating mechanical vacuum pumps offer substantial savings over the whole melt weight range up to 360 t. Such savings differ for the various processes and depend upon the availability of energy as well as upon plant productivity. The shortening of the treatment cycle time by a rapid pump down limits melt overheating and thus leads to savings in production cost, increased productivity and quality improvement.

Die Umwandlungskosten für Stahl in sekundärmetallurgischen Anlagen, bestehend aus einem Pfannenofen und verschiedenen Vakuumbehandlungsverfahren, werden für einen breiten Gewichtsbereich an Schmelzen untersucht. Hierbei werden zwei allgemein verwendete Vakuumpumpensysteme verglichen. Trocken arbeitende mechanische Pumpen bieten beträchtliche Einsparungen für alle Schmelzen von bis zu 360 t. Diese Einsparungen variieren für die verschiedenen Vakuumverfahren und hängen von der Verfügbarkeit der Energie sowie von der Anlagenproduktivität ab. Die Verkürzung der Behandlungsdauer durch schnelles Abpumpen führt zu Einsparungen an Behandlungskosten, Produktivitätserhöhung und Qualitätsverbesserung.

The revival of dry operating mechanical vacuum pumps for use in steel degassing is due to their proven reliability during the past 30 years, increased environmental consciousness, the push-button availability of vacuum, low operating cost [1 … 7], excellent quality results [3 … 10] and their suitability for all kinds of processes in secondary steelmaking [9 … 12].

Vacuum treatment in the teeming ladle in presence of active slag does not only result in low gas, sulphur and zinc contents but also leads to a better castability [8]. This has pushed vacuum treatment to many applications each time there are casting nozzle clogging or surface problems. The advantages of mechanical vacuum pumps [1 … 10] have shifted their use also to larger melt sizes that before had been degassed exclusively with steam ejector systems.

In the following the cost structure of secondary metallurgy is investigated including a ladle furnace using two distinctive vacuum systems.

The criteria compared are

- energy and fluids consumption
- maintenance, cleaning, disposal and spare cost
- overheating cost in the ladle furnace.

Modern pump set for VD plant at BGH Siegen in Germany

VD-Anlage bei BGH in Siegen

Photo: Oerlikon-Leybold-Vacuum

Common basis for comparison

The cost structure is investigated for VD tank degassing for heat sizes from 25 to 360 t that frequently becomes VCD tank degassing for the larger heat sizes, as well as for VCP (RH) degassing from 80 to 360 t.

Low alloyed steel grades and super-alloys that aim at low carbon contents need oxygen injection under vacuum. This has led to process varieties like VID-OB, VD-OB, VCP/RH-OB and RH-TOP and for high chromium alloyed grades to the processes VOD, SSVOD and VODC. They are all possible with any pump system.

The compared vacuum pump systems are

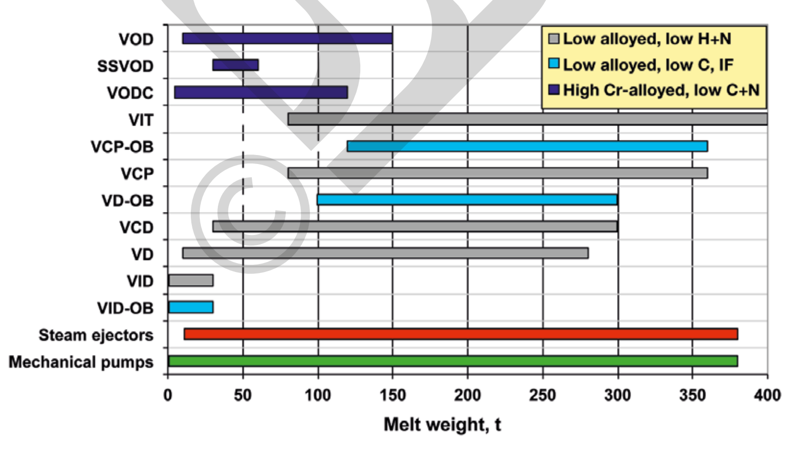
- modern steam ejector systems combined with water ring pumps,
- dry mechanical pump sets. They have a traditional multi-stage layout with screw pumps as primary pumps, whereas the fine vacuum pumps are twin-lobe Roots blowers.

The ranges of melt sizes, processes and pump systems are shown in figure 1. This figure shows that both vacuum pump systems can be used for all processes and wide heat ranges.

Specific cost factors

Various specific cost factors will be described now.

Steam. Steam is a by-product in integrated steel plants since it is generated by the evaporation of cooling water for converter hoods, staves of blast furnaces and recently also off-gas ducts and side panels of electric arc furnaces. The cooling water of these elements must be clean and softened as is the boiler water in case steam is generated separately to serve as the driving gas of steam ejectors.



1

Range of melt sizes, vacuum processes and vacuum pump systems

Bereiche der Schmelzgewichte für Vakuumverfahren und Vakuumpumpensysteme

The steam must in all cases be overheated and kept in the overheated state in order to prevent condensation and premature nozzle wear of the steam ejectors.

Steam as a by-product is reported to cost 8 to 10 €/t of steam, such cost being caused by the means for storage, overheating and isolation [10].

However, when overheated steam is generated by a fossil energy-fuelled boiler it will cost 22 to 30 €/t of steam. This cost includes the fuel, the boiler water treatment, the fuel storage and supply system but not the boiler attendance and supervision and the capital cost.

Also one has to add 10 – 12 % to the steam cost for CO_2 emission rights on the basis of 20 €/t of emitted CO_2 per year.

The above cost figure does not, however, reflect the effective steam cost per ton of steel. Since steam is not available on a push-button base, any boiler must be kept running at low fire in between the vacuum heats and must be brought to full power some minutes before the maximum steam flow is requested for quick pump down at the beginning of any vacuum treatment cycle.

The effective steam consumption therefore depends strongly upon the productivity of the plant.

Condenser water (contact water). The quantity of water needed for steam condensation in spray condensers and in water ring pumps depends upon the amount of steam to be condensed but also strongly upon the water temperature.

In general the water inlet temperature must never exceed 35 °C, otherwise the pump performances and thus the ultimate vacuum pressure will suffer.

The quality of this condenser water may, however, be very poor in terms of turbidity, hardness and chlorine content. Many steam ejector systems operate on the basis of sea water with provisions for corrosion resistant material.

The temperature increase is between 10 and 12 K only, but compared to other pump systems the total heat content of the system is high. Not only the heat as generated by the gas compression, but also the whole energy contained in the overheated steam must be removed by a suitable cooling system.

This water is also in contact with the process gas that beside the dust load contains large amounts of CO. Therefore the cost of this kind of water is generated by circulation pumps, sludge pumps, cooling tower fans, CO scrubbers and fans for forced ventilation of hot well and off-water channels as well as by make-up water (~5 %).

Non-contact cooling water. This kind of water is only used for dry operating mechanical vacuum pumps.

It is needed for the bearing cooling of larger Roots pumps, for the motor cooling of modern small Roots pumps [10], for inter-stage air-water heat exchangers and for the cooling of pump casings of primary pumps. These latter pumps like screw pumps, claw pumps, multistage-trilobe Roots pumps etc. operate with a high internal compression rate and therefore develop an elevated temperature.

But the total amount of water and the heat development in any mechanical pump set are low compared to steam ejector systems. Therefore this water can be kept in a pressure closed circuit and may be equipped with a simple secondary cooling system. The running cost of this cooling water is governed by small circulation pumps and cooling devices.

Electric energy. One should distinguish between the electric energy as absorbed by the vacuum pumps, the water circulation pumps and other auxiliaries like cooling compressors, fans of evaporation towers etc. and the electric energy used for melt overheating in the ladle furnace.

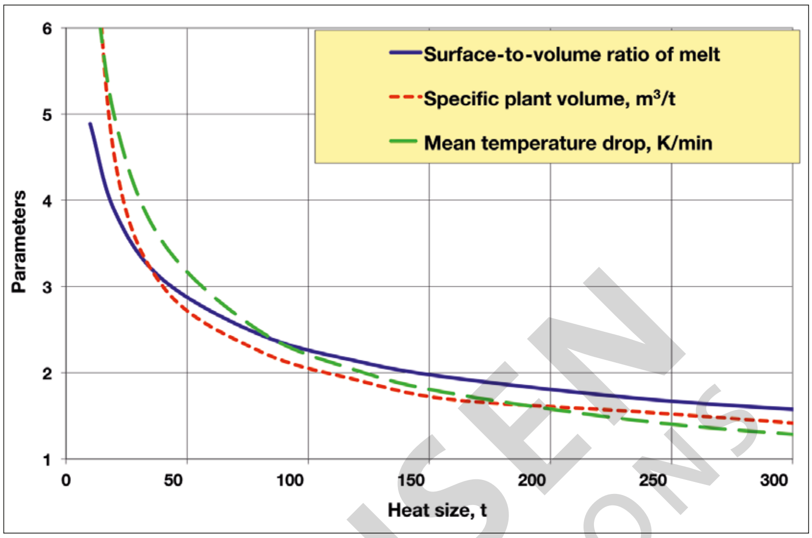
Electric energy cost ranges from 30 to 120 €/MWh depending upon the local energy mix and the hours during which the energy is used. Many steel works have managed to have electric energy available for a mean cost of 40 to 75 €/MWh.

Compressed air consumption is very low since it is used only for valve controls and sealing seat cleaning in the same way for all considered vacuum pump systems.

Nitrogen is used for dust removing from filter bags as well as ballast gas in some mechanical pumps for oxidizing vacuum processes (VOD, VD-OB etc.). The kind of supply either in bottles or by an evaporator determines the nitrogen cost.

Argon is also taken into account. The specific argon flow rate varies from 1 to 8 dm³/min/t for the various processes but is independent of the pump system used.

Oxygen is used for vacuum processes with an oxidizing phase like VOD, VD-OB etc. Its consumption depends upon the amount of elements to be oxidized, the oxygen yield offered by the plant layout and the process, but does not vary with the pump system used.



2

Temperature drops and parameters affecting heat losses during vacuum treatment in ladles

Temperaturverluste und Einflussfaktoren für Wärmeverluste bei der Vakuumbehandlung in Pfannen

Gear box oil is needed for the dry operating mechanical vacuum pumps only. Its consumption is very low and the cost incidence is negligible.

Maintenance. It is assumed that for most of the steel plants the maintenance cost for the various energy and fluid supplies is included in the cost or usage value of these items.

Therefore only the special maintenance for steam boilers, steam ejectors, rotating pumps and dust filters has been considered. This includes permanent supervision for steam boilers, dust extraction from a dust filter, weekly inspections, quarterly cleaning and yearly exchange of wear items like filter bags.

Disposal. Disposal of dry dust and of sludge is an increasingly important cost factor. In dry operating mechanical pumps only dry dust is formed that is extracted from the dust collector and can be added to other dust and scale as co-products of the plant.

The disposal cost is often equal to the transport cost. If, however, the dust does not contain valuable elements then its disposal may cost as much as 120 – 180 €/t.

This cost will be much higher when the abated dust is watered and forms sludge. This is the case in all steam ejector systems.

The sludge water needs a long separation time by floating and the concentrated sludge would require an energy and time consuming drying before any valourization.

Spares. No vacuum pump system has a significant consumption of spares.

In steam ejector systems these might be the steam nozzles in case the humidity content of steam is too high. Steam ejector systems have in general a wear allowance of 3 to 4 mm in order to cope with erosion and corrosion.

In many systems with dust abatement by cloth filters, the bags should be inspected and replaced once a year or after 10 000 operational hours.

Overheating cost. The most important cost factor related to any vacuum treatment is the overheating of the melt in the ladle furnace in order to compensate the heat losses during the subsequent vacuum treatment.

In VCP (RH) plants the heating of the circulation vessel is also to be taken into account.

Without any vacuum treatment the ladle furnace energy consumption is ~60 kWh/t provided the ladle is in operational turn or suitably preheated and the alloying additions do not exceed 20 kg/t.

The graphite electrode consumption may be as low as 0.5 kg/t while the argon flow is ~1 dm³/min/t.

For any vacuum treatment the overheating requires additional energy of 0.41 – 0.45 kWh/t/K with the corresponding additional consumption of electrodes and argon.

The residence time of the melt in the ladle, the maximum heat temperature and the slag composition are important factors for the lifetime of ladle lining.

Short idle times including pump-down reduce both the maximum overheating temperature and the residence time of melt and slag in the ladle.

Importance of short pump-down times

A particular vacuum plant concept has been developed recently [11]. By the intelligent choice of pump type and size, number of pressure stages and pump engagement sequence, pump-down can be shortened by 2 – 3 min, i. e. ~10 % of the total VD treatment time, compared to many steam ejector systems and also with respect to more conventional sets of mechanical pumps [3; 5].

Such time saving is very helpful since it limits the temperature losses, increases the filter bag life time avoiding dust ignition, may affect the quality via the reactions with the lining, leads to lower final C-contents [12 …14] and in some cases helps to increase productivity. This time saving is obtained through a rather high energy input during the pump-down phase.

Cost criterion		Condition	Specific cost		Steam ejectors with WRP				Dry mechanical pumps including dedusting				Saving by MP		
Consumption															
- steam		12 bar, 194°C	25,00	€/t	42,5	kg/t	1,062	€/t							
- CO_2 emission rights			20,00	€/t	6,3	kg/t	0,125	€/t							
- boiler water			0,100	€/m³	0,04	m³/t	0,004	€/t							
- contact water		3 bar, 32 °C	0,020	€/m³	1,00	m³/t	0,020	€/t							
- non-contact water		4 bar, 32 °C	0,035	€/m³					0,054	m³/t	0,002	€/t			
- compressed air		5 bar	0,005	€/m³	0,004	m³/t	0,000	€/t	0,004	m³/t	0,000	€/t			
- nitrogen		12 bar	0,100	€/m³					0,060	m³/t	0,006	€/t			
- argon		12 bar	0,600	€/m³	50,00	dm³/t	0,030	€/t	46,00	dm³/t	0,028	€/t			
- gear box oil			5,00	€/dm³					0,001	dm³/t	0,003	€/t			
- power for vacuum pumps			0,045	€/kWh	1,04	kWh/t	0,047	€/t	1,218	kWh/t	0,055	€/t			
- power for water pumps			0,045	€/kWh	0,21	kWh/t	0,009	€/t	0,010	kWh/t	0,000	€/t			
- power for auxiliaries			0,045	€/kWh	0,22	kWh/t	0,010	€/t	0,010	kWh/t	0,000	€/t			
Subtotal consumption							1,307	€/t			0,094	€/t	1,21	€/t	75%
Maintenance											1				
- boiler attendance							0,106	€/t							
- monthly pump cleaning	8	man-hours	20	€/h	455	heats	0,000	€/t							
- yearly pump cleaning	30	man-hours	30	€/h	5000	heats	0,002	€/t							
- filter bag inspection	2	man-hours	20	€/h					100	heats	0,000	€/t			
- filter bag changing	8	man-hours	20	€/h					5000	heats	0,000	€/t			
- dust disposal			170	€/t dust	0,02	kg/t	0,003	€/t	0,22	kg/t	0,037	€/t			
- sludge disposal			240	€/t dust	0,20	kg/t	0,048	€/t							
Spares															
- filter bags	8000	hours	7	€/m²					5000	heats	0,005	€/t			
Subtotal maintenance+spares							0,160	€/t			0,042	€/t	0,12	€/t	7%
Overheating and ladle							**65**	**K**			**59**	**K**			
- refractories	45	heats	1,20	€/kg	6,8	kg/t	8,14	€/t	6,6	kg/t	7,98	€/t	0,16		
- argon		12 bar	0,60	€/m³	96	l/t	0,06	€/t	92	l/t	0,06	€/t	0,002		
- electric energy			0,045	€/kWh	47,0	kWh/t	2,11	€/t	44,9	kWh/t	2,02	€/t	0,095		
- electrodes			2,34	€/kg	0,35	kg/t	0,82	€/t	0,34	kg/t	0,79	€/t	0,037		
Subtotal overheating							11,13				10,84		0,30	€/t	18%
TOTAL							12,60	€/t			10,97	€/t	1,63	€/t	100%
Annual saving		**425.000**		**t/a**									**692.000**		**€/a**

3

LF/VD conversion cost for a 85-t melt and a VD cycle of 23 min

LF/VD-Umwandlungskosten für eine 85-t-Schmelze und einen VD-Zyklus von 23 min

Any rapid and easy to control pump-down should only be performed down to a pressure at which heavy boiling reactions by degassing, evaporation or decarburisation start. Such pressure ranges are ~400 hPa for Zn-polluted melts, ~300 hPa for unkilled steel grades, <200 hPa for the VOD process and ~70 hPa in killed melts covered by an active slag, or <10 hPa when the slag is completely missing as in Vacuum Induction Degassing (VID).

Figure 2 shows that for heats ranging from 10 to 300 t and ladle shapes permitting a bath H/D-ratio of 1:1, the surface-to-volume ratio (S/V) drops from 8 to 1.5. As a consequence the empiric mean temperature losses per minute are as high as >6 K/min for small heats and drop down to <1.2 K/min for the largest heats.

In parallel to these heat losses by radiation it happens that the specific VD tank plant volume necessary for small heats is rather large with a value of 8 m^3/t for a 10-t heat, but that it decreases to ~1.5 m^3/t for a 250-t heat.

As a consequence of these heat-loss-affecting parameters a short pump-down is an important factor for smaller heats for which the temperature losses are high because of the larger ratio of surface to volume (S/V) and for which the specific plant volume is also relatively large.

As an example a pump of 120 000 m^3/h capacity for a 90-t heat and a plant volume of 250 m^3, a pressure of 100 hPa can be reached within 100 s. Compared to plants with steam ejectors or also compared to more conventional plants with dry mechanical pumps [3; 5] these performances mean a time saving of 2 min. With a mean temperature loss of 2.5 – 3.0 K/min the avoided temperature drop would be 5 – 6 K.

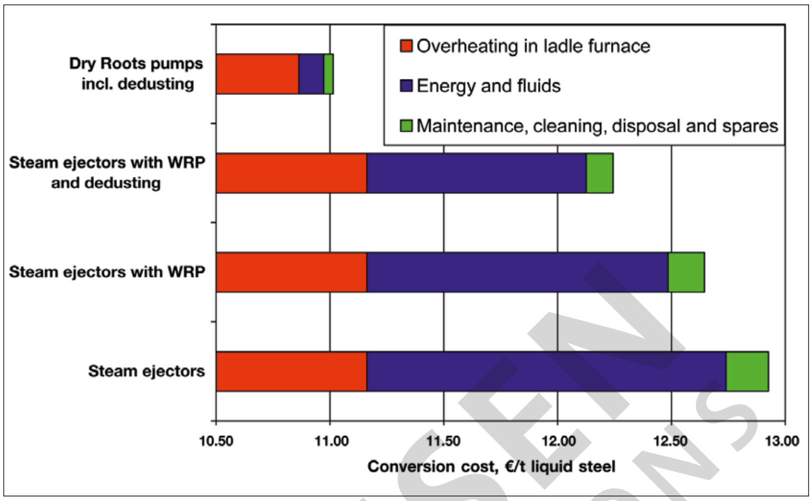
The ladle furnace preceding the vacuum plant must overheat the melt to compensate this loss.

A moderate ladle furnace temperature is, however, recommended since lining wear is enhanced by the active desulphurizing slag.

Last but not least the steel quality is indirectly affected by melt overheating. In all ladles with a basic MgO lining an oxide reduction occurs that is reinforced under the effect of high temperatures and of vacuum since CO is formed. The formed Mg will be re-oxidized by dissolved oxygen. Since such re-oxidation occurs in the slag and in the melt, the newly formed MgO may generate spinel-type inclusions that are difficult to remove.

Savings in the VD and the VCD process

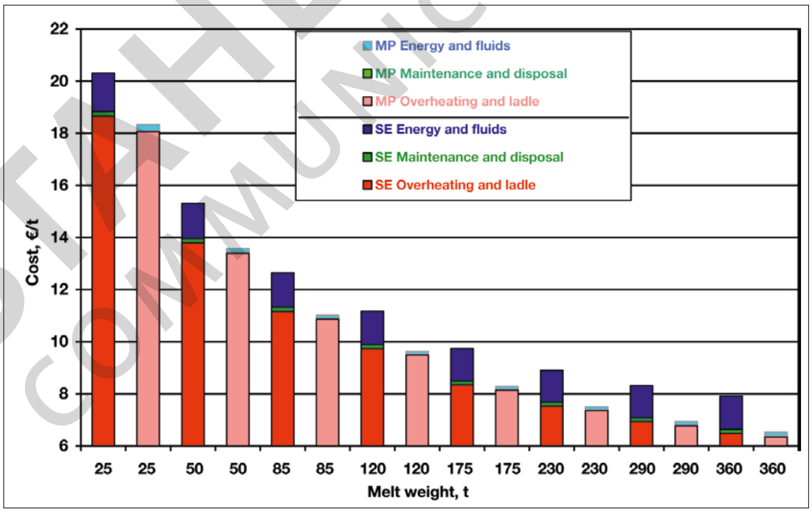
The specific cost for energy, fluids, electrodes and refractory material vary according to local supply conditions. They depend to a large extent upon the yearly consumed quantity. In this respect larger production units obtain better purchasing conditions on the market more easily than smaller plants.



4

Cost structure for vacuum degassing (VD) including ladle furnace treatment (LF) in various vacuum pump systems

Kostenaufbau der Vakuumentgasung (VD) einschließlich Pfannenofenbehandlung (LF) für verschiedene Vakuumpumpensysteme



5

Cost structure for LF/VD process for various heats sizes and vacuum pump systems

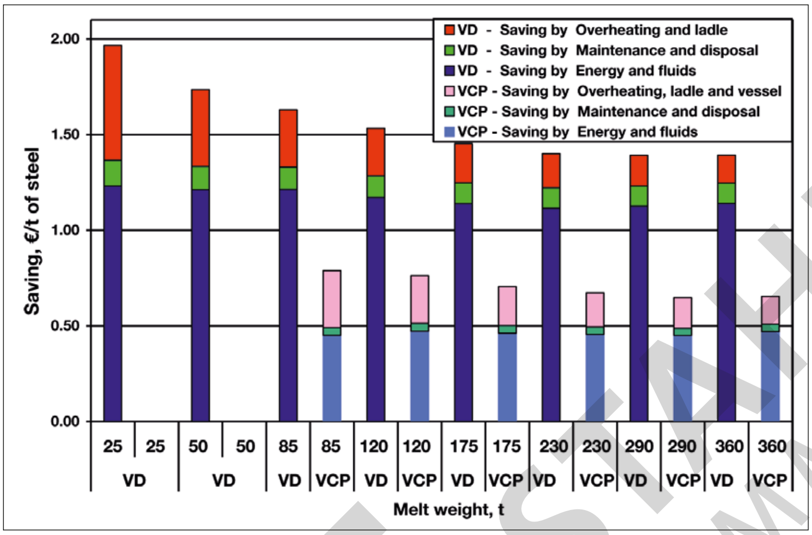
Kostenaufbau im LF/VD-Verfahren für verschiedene Schmelzengewichte und Vakuumpumpensysteme

Here it is therefore tabled on the specific cost that are applicable for most of the steel plants in central Europe running plants with a heat size of 50 to 100 t and with an annual vacuum-treated production of 250 000 to 500 000 t.

An example of cost structure for an 85-t heat and various vacuum pump systems is given in figure 3 and figure 4.

The savings in the above example of 85-t heats offered by mechanical pumps against any type of steam ejector system are of course higher for smaller heats and smaller for larger heat sizes. The reasons are not only the purchasing conditions but also the influence of heat losses, the specific plant volume and the general “law of size” that is applicable for any industrial plant as demonstrated by figure 2.

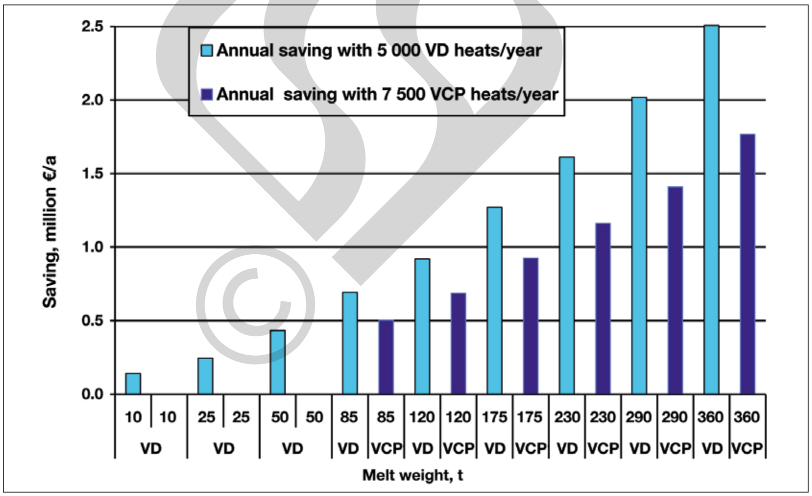
Based upon the same specific cost for the various items we have calculated the total LF/VD cost for heats ranging from 25 to 360 t and for the most modern layouts of the two vacuum pump systems.



6

Savings offered by dry mechanical vacuum pumps for typical VD and VCP plants

Durch trocken laufende Vakuumpumpen ermöglichte Ersparnisse in VD- und VCP-Anlagen



7

Annual savings as offered by dry operating mechanical pumps for the VD and the VCP/RH process

Durch trocken laufende Vakuumpumpen ermöglichte jährliche Ersparnisse beim VD- und VCP/RH-Verfahren

For boiler-generated steam systems the cost difference only for energy plus fluids consumption is always the major part of the total saving that is offered by dry mechanical pumps. It may be <60 % for a 25-t heat and rise to >80 % for a 360-t heat.

It is interesting to state that the steam ejector systems combined with water ring pumps have a higher electric energy consumption than dry operating mechanical vacuum pumps for systems with comparable suction capacity when all necessary auxiliary equipments are taken into account.

The savings offered in the field of maintenance and cleaning of the steam generators, vacuum pumps, filters and coolers, disposal of dust and sludge as well as exchange items remain nearly same with about 7 % over the whole range of heat sizes.

The savings in overheating cost at the ladle furnace are strictly related to the shortening of pump-down time as this is possible with the concept of the Ventus system [11].

The cost savings by this rapid pump-down range from >0.60 €/t for the smallest heats to <0,15 €/t for the largest heats.

Such savings made by rapid pump-down are to be paid by a slightly higher energy consumption that is generated by the directly exhausting pumps and their strong motors. However, this high energy absorption is restricted to the short pump-down time and therefore stands for only <0.1 kWh/t. Thus the extra energy cost of <0.01 €/t is fairly paid off by the saving even if one considers any capital cost for a slightly higher investment.

It is noteworthy that a VD cycle for a 25-t heat is considered here to last 12 min while the extended cycle of VCD followed by a VD treatment of a 360-t heat may last up to 35 min.

The absolute cost figures for the two vacuum systems are given in figure 5, while the savings as offered by dry operating mechanical vacuum pumps are given in figure 6. In this figure the savings in static tank degassing VD are compared to those that can be realized in dynamic degassing according to the VCP process that may take profit of the cheap availability of steam in integrated steel plants.

Savings in the VOD process

In the VOD process for high Cr-bearing steel grades and super-alloys the savings in energy and fluids are much higher than in the VD or VCD process, since the treatment cycle is four to five times longer with a resulting higher consumption in steam, water and electric energy [1].

Since the strong formation of dust would generate considerable trouble and disposal cost, the steam ejector systems are in many cases also equipped with dust filters. In this case the cost for maintenance, cleaning and disposal are the same for all pump systems.

The savings in melt overheating disappear since VOD is an exothermic process.

Savings in the VCP (RH) process

VCP/RH plants are frequently in line with a BOF that supplies steam at low cost as a by-product. Also these plants are designated to high productivity which considerably shortens the stand-by time of any steam supplying unit. Thus the specific steam consumption is lower in the VCP/RH compared to the VD process.

The savings in maintenance, cleaning, disposal and spares are the same as in the VD process unless the steam ejectors which are also protected by a filter, disappear.

The VCP/RH process with its additional circulation vessel engages much more refractory material compared to any VD plant even with its high ladle freeboard.

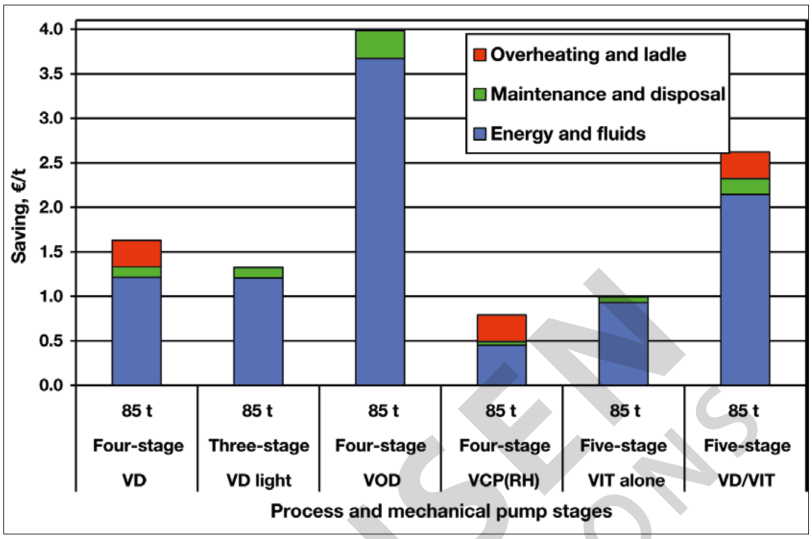
The resulting highly specific ladle plus vessel cost are the price to be paid for the outstanding features of the VCP/RH process in terms of productivity, low gas contents and low carbon content [17].

In general the total savings as offered by dry mechanical vacuum pumps are – in the case of by-product-steam – only half of the savings reached in the classical VD process as shown in figure 6.

The annual savings, however, are only cut by one third as demonstrated in figure 7. This is due to the other cost factors and the higher productivity of VCP plants.

Savings in steam degassing

Dry operating mechanical vacuum pumps are ideal for steam degassing according to the Vacuum Ingot Teeming (VIT) process with metal flow rates up to 8 t/min. In fact this process requires a high mass flow capacity of the vacuum pump in a low pressure range like 0.2 – 0.3 hPa. This requires a five-stage design for the steam ejector system while a three-stage design would be sufficient with dry operating mechanical pumps. In melt shops that are designated to VIT the steam is generated by a stand-alone boiler. The high mass flow at low pressure and the rather small production and productivity make steam consumption very effective including the long stand-by times. In this respect the push-button availability of mechanical vacuum pumps is an outstanding advantage.



8

Savings as offered by dry operating mechanical pumps in different vacuum processes for the same melt weight of 85 t

Durch trocken laufende Vakuumpumpen ermöglichte Ersparnisse in verschiedenen Vakuumverfahren bei gleichem Schmelzengewicht von 85 t

Thus the savings in energy and fluids offered by the mechanical pumps are much higher than in the VD, VCD or VCP/RH processes.

There are no substantial savings in the cost for maintenance, cleaning, disposal and spares since the quantity of generated dust is small.

Since fast pump-down is immaterial for this process there are no savings in overheating cost. The savings made in the VD treatment that precedes the VIT process remain, however, fully valid and add to the VIT savings as shown in figure 8. For comparison's sake a very small melt size has been chosen for the ingot to be teemed under vacuum. For the commonly teemed large ingots of over 160 t of weight and the projected ingots of 400 to 600 t the savings offered by dry operating mechanical vacuum pumps are higher of course.

Conclusions

Dry operating mechanical vacuum pumps made a significant progress in the past ten years for heats up to 230 t. There are no limits in suction capacity or process applicability, while the savings are still substantial for highest melt weights.

Comparative figures for savings as offered by dry operating mechanical vacuum pumps for a 85-t heat for different processes are given in figure 8.

Since varying local conditions may considerably affect operating cost for a vacuum treatment the steelmakers are invited to make an individual cost study taking into account the local availability of various energy forms, purchasing possibilities, plant productivity and environmental requirements. Recently a profitability study [16] was made for Chinese conditions and the local currency for melts ranging from 12 to 150 t. Similar investigations taking into account the special local conditions could be made in cooperation with an independent engineering office.

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