Metall. Res. Technol. **111**, 119–128 (2014)
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DOI: 10.1051/metal/2014023
www.metallurgical-research.org

&Metallurgical Research Technology

Selection of vacuum pump system for steel degassing

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Key words:
Steel degassing; Steam ejector vacuum pumps; mechanical vacuum pumps

Abstract – Steam ejector vacuum pumps (SVPs) are mainly used on larger melt sizes up to 350 t in integrated steel plants because of the availability of steam. The use of dry operating mechanical vacuum pumps (MVPs) for steel degassing has made a tremendous step forward in the past 10 years but is still confined to melts below 150 t while its progress towards larger melt sizes is not completed. Besides the consideration of investment and operating costs there is no restriction in using any type of modern vacuum pump system for all vacuum processes and plant designs. Both systems fulfil all metallurgical requirements. Considering the significant savings in operating cost offered by MVP systems it is worth reconsidering the efforts for reducing air leaks, the use of protective gases and pressure losses between the pump set and the metallurgical reaction vessel. Both systems have made progress in energy optimising but the MVPs have a striking energy advantage. Only the overall costs should be considered, including those necessary to meet emission constraints and safety standards, and only the pressure prevailing at the reaction vessel is to be considered when comparing vacuum pump systems. Also, the means and use of dust abatement systems should be reconsidered since they offer cost savings by reducing the frequency of cleaning, less wear, little sludge handling and the significantly lower design suction capacity of SVP systems. The SVP mass flow need is to be corrected by a special coefficient before being applied to the volume conveying MVPs. Depending on the operational pressure required for the pump design, MVP systems can reach the same performance at the reaction vessel with much less mass flow capacity than that needed by a SVP system.

Mots-clés :
Dégazage d'aciers ; pompes d'ejecteur à vapeur ; pompes mécaniques à vide

Résumé – Choix de pompes à vide pour le dégazage d'aciers. Les éjecteurs à vapeur (SVP) sont utilisés dans les aciéries intégrées comme pompes à vide, surtout à cause de la disponibilité en vapeur et pour des capacités de poches de coulées allant jusqu' à 350 t. L'utilisation de pompes mécaniques à vide (MVP) travaillant à sec a fait un progrès impressionnant dans la dernière décennie pour le dégazage des aciers mais se trouve encore limitée pour les capacités de poches de coulée en dessous de 150 t bien que la course vers des capacités plus importantes ne soit pas terminée. À part les considérations relatives aux investissements et aux frais opérationnels, il n'y a pas de restriction à utiliser un type de pompe ou un autre quels que soient les procédés de traitement sous vide et la conception des installations. Pour obtenir des économies importantes sur les frais opérationnels il faut prendre la peine de réfléchir sur les efforts à faire pour la réduction des fuites d'air, l'utilisation de gaz de protection et la valeur des pertes de charge entre la pompe et le réacteur métallurgique. Les deux types de pompes ont fait des progrès en réduisant les besoins en énergie mais les MVP ont un avantage frappant dans ce domaine. Cependant ce sont les frais totaux qui devraient être considérés, y compris ceux qui sont nécessaire pour respecter les limites des émissions et les normes de sécurité, bien que la pression régnant dans le réacteur reste le critère de comparaison le plus important quand on compare les deux types de pompes. Les moyens de récupération des poussières et leur mode opératoire doivent être repensés en recherchant des réductions de frais liés aux nettoyages en réduisant leur fréquence, à une moindre usure des organes, à la gestion des boues ainsi qu'au niveau de la capacité d'aspiration qu'imposent les SVP. Le flux de masse extrait par les SVP doit être corrigé d'un facteur spécial avant de l'appliquer à celui extrait par les MVP. Selon la pression opérationnelle choisie les MVP peuvent obtenir les mêmes performances au réacteur métallurgique avec bien moins de capacité de flux massique que celles nécessitées par les SVP.

Received 19 November 2013
Accepted 30 April 2014

https://doi.org/10.1051/metal/2014023 Published online by Cambridge University Press
Article published by EDP Sciences

Mechanical vacuum pumps (MVPs) were the first to be used on an industrial scale for steel degassing in the late fifties but their use is still confined to smaller heat sizes below 150 t with some exceptions, and with strong tendencies to be used for larger heat sizes.

MVP stands here for dry operating pumps excluding water ring pumps and oil-sealed pumps.

Steam ejector vacuum pumps are concentrated on the larger melt sizes up to 350 t mainly in integrated steel plants because of their availability of steam.

Both systems have been proven in an industrial capacity for all kinds of vacuum processes such as ladle degassing, tank degassing (VD), stream degassing (VIT), Vacuum Oxygen Decarburisation (VOD), and Vacuum Circulation Degassing without (RH) or with oxygen blowing (RHO).

Besides the low steam cost, a lack of environmental consciousness and the cost externalisation for cleaning, sludge and dust handling has for a long time been detrimental to the development of the MVP, also for larger heat sizes in spite of their proven long term-reliability and their undisputed, mainly energy-related advantages in operating cost [1–3].

Figure 1 shows the number of MVP systems and the tendency to larger melt sizes.

While selecting a vacuum pump all aspects should be considered such as space requirement, availability of energy and fluids, the breakdown concept, the production interruptions for cleaning and maintenance, the necessary auxiliary equipment and the costs of meeting emission rules and safety standards.

1 Typical layouts

Steam ejector systems (SVP) have made progress regarding steam consumption by introducing water ring pumps (WRP). A typical SVP today is a four-stage arrangement consisting of three ejector stages and WRP stage. In cases where the condenser water temperature is between 30 and 35 °C, one more ejector stage has to be added as shown in Figure 2.

This figure shows the schematic build-up of a modern SVP system and explains why the electric energy consumption of such systems could be higher than in MVP systems of equal performance because of the strong WRP and all the necessary auxiliary equipment for water circulation and cooling, sludge handling, and hot well venting [1–5].

The MVP systems commonly have 3 or 4 stages using endless screw primary pumps, exhausting to atmosphere and Roots blowers for the high-volume flow units.

The differences in the various MVP configurations are in the capacities of all the direct-exhausting pumps such as primary and intermediate gas-cooled pumps, in the size and number of different types of pumps, the kind of motor connection [6–8], the need for heat exchangers, etc. Also, there is a redundancy concept, nearly unknown for SVP, and the ease and flexibility of coping with different process situations such as rapid or controlled pump-down, constant volume flow and oxygen blowing in the metallurgical vessel. These are the main features in which MVPs from various suppliers differ.

A very important difference lies in the choice of either a high number of small pumps with low mass inertia or a few large pumps with high inertia [7, 8]. The largest Roots pumps presently on the market have about 80 000 m^3/h effective capacity and a high inertia. This makes them sluggish and therefore not suitable when large suction capacities are to be established rapidly for high-productivity units such as RH and RHO plants or whenever any pump-down modulation or pressure control is required.

Figure 3 shows the schematic build-up of a modern 3-stage MVP in a modular build-up.

All types of vacuum pumps have to fulfil the same tasks which include:

- **quick pump down** to a pressure at which intensive degassing reactions start;
- **controlled pump down** in medium pressure ranges from 300 to 10 hPa depending on the degree of deoxidation and the amount of dissolved gases;
- **maintaining a volume flow** nearly constant under the high gas load conditions generated by oxygen blowing;

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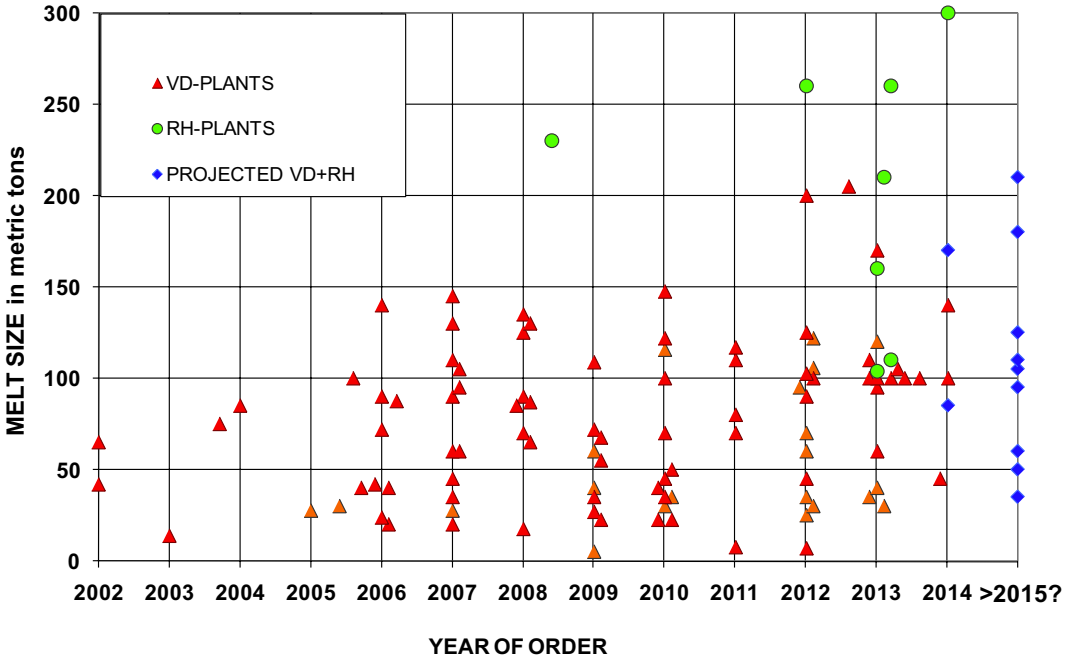


Fig. 1. Melt sizes treated with mechanical vacuum pumps in VD/VOD/RH plants worldwide since 2002.

Fig. 1. Poids des coulées traitées avec des pompes à vide mécaniques dans des installations VD/VOD/RH depuis 2002 dans le monde entier.

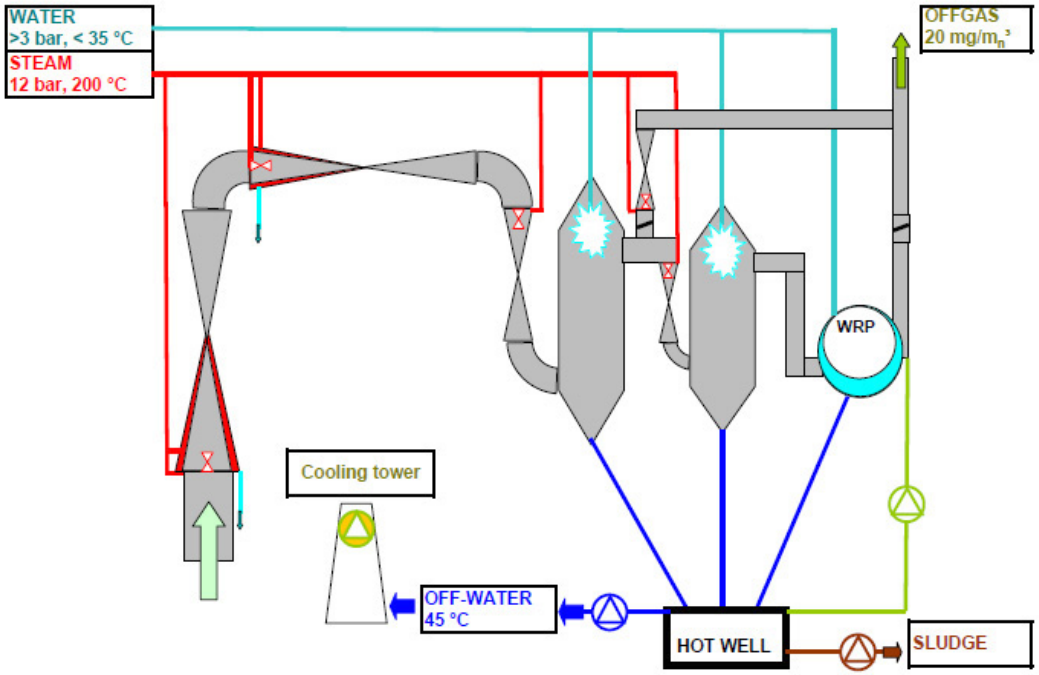


Fig. 2. Sketch of a typical steam ejector system with its necessary auxiliary equipment.

Fig. 2. Schéma type d'un système à éjecteurs à vapeur avec tous son équipement auxiliaire nécessaire.

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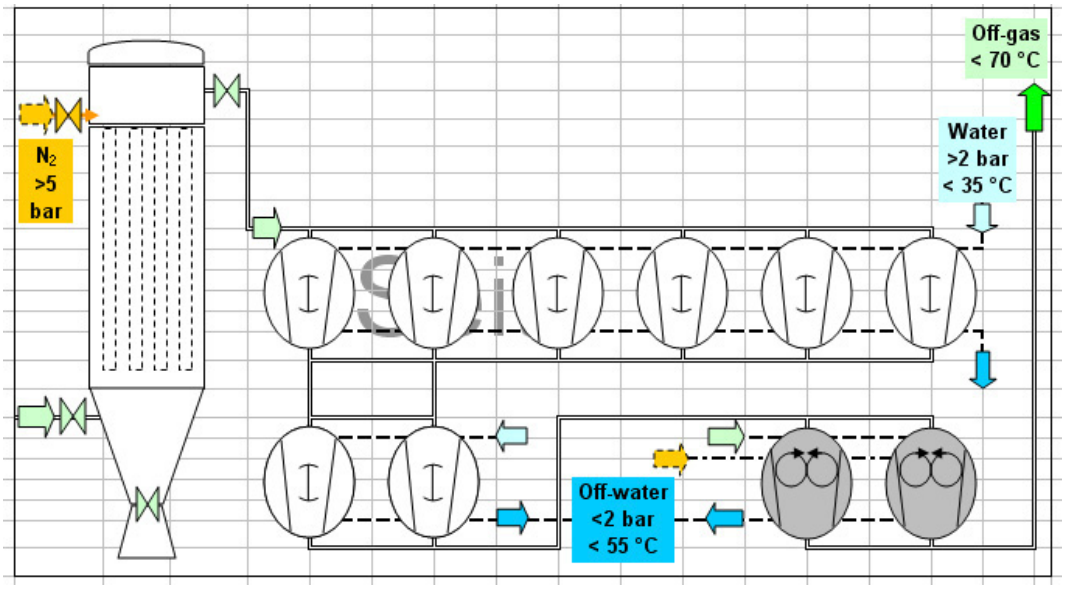


Fig. 3. Sketch of a 3-stage MVP module with dust filter.
Fig. 3. Schéma d'un module de pompes mécaniques à 3 étages avec filtre à poussière.

– **reach a low pressure** at the end of the treatment cycle depending upon the argon flow rate used in degassing by purging or for lifting and stirring.

Such tasks have to be fulfilled under more or less heavy gas loads that do not contribute to the metallurgical targets such as air leaks and the use of protective gases to keep clear observation ports and burners or blowing lances when in stand-by position.

2 Auxiliary equipment that is needed for any pump system

Any vacuum pump system is only as good as its auxiliary equipment for gas cooling, prevention of explosion hazards, dust abatement and dust extraction. The auxiliary equipment related to the two pump types is very different today but subject to development.

All MVPs do in fact need dust abatement for all processes and gas cooling for RH plants and for the oxidising treatments such as VD-OB, RHO and VOD.

For SVP this is required only for the latter processes. However, dust abatement is useful for all vacuum processes using SVP since it offers cost savings by reducing the frequency of ejector cleaning, results in less wear, eliminates sludge handling and enables a lower design suction capacity compared with SVP systems without dust abatement.

One of the main differences in the pump systems lies in the fact that MVPs cannot accept gas inlet temperatures typically over 60 °C whereas SVP systems admit gases as hot as 250 °C at the SVP inlet.

The connection line between vessel and vacuum pump generates a considerable pressure drop that cannot be neglected when determining the need for suction capacity and for the pressure to be reached at the reaction vessel.

Such pressure drops may annihilate 10% of the installed suction capacity for plants of heat sizes below 30 t, and may exceed 40% in plants for heats over 300 t.

Another important difference lies in the capability to handle dust-laden gases. For a MVP such a gas load is rather restricted, but the SVP can carry the unfiltered gases even while this generates some important disadvantages including ejector clogging, erosion, sludge formation etc. To reduce these handicaps some SVP systems also have off-line cyclones or in-line filters.

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Table 1. Equipment required for various pump types and processes.

Process	VD		VD-OB		VOD		RH		RHOB	
	SVP	MVP	SVP	MVP	SVP	MVP	SVP	MVP	SVP	MVP
Suction pipe										
- uncooled	•	•					•		•	
- refractory lined	(o)								(o)	
- water cooled			•	•	••	••	•	•	(o)	•
Dust catcher	•		•		•	•	•	•	••	••
Cyclone			•	•	••	••				
Gas cooler			•	•	••	••	(o)	(o)	•	•
Bag filter	•	•	(o)	•	(o)	•	(o)	•	(o)	•
Bath observation	(o)		(o)		(o)		(o)		(o)	
ATEX equipment	(o)	(o)	•	•	•	•	(o)	(o)	(o)	•
Cleaning	•		••		•••		•		••	
Dust handling	•	•	•	•	••	••	•	•	•	•
Sludge handling	•		•		••		•		••	
Water treatment	•		•		•		•		•	
Steam handling	•		•		•		•		•	

••• , ••, • more or less required (o) recommended depending on the case.

The various system-related equipment is listed in Table 1.

Comments on Table 1:

- Suction pipes should be refractory lined or partially water-cooled only for all oxygen blowing processes that generate CO, in case the post-combustion cannot be controlled.
- Dust abatement requires a "dust catcher" for the coarser grain particles and spatter in all processes in which vigorous reactions caused either by intensive use of argon or by oxygen injection take place. Further dust abatement by means of a cyclone is needed for all oxygen blowing processes in order not to overload the down-line bag filter. Additional gas cooling is necessary each time CO is formed by forced decarburisation and the gas temperature must be cooled to the temperature admitted for bag filters (<120 °C) or for the pump system (<250 °C for a SVP or <60 °C for a MVP).
- Bath observation is not specific to any pump system. It becomes obsolete with a steel grade specific pump down programme which is easily established by frequency modulation of the pump motors of MVPs or in a general way by off-gas ballasting.
- ATEX (explosion safety) certificates are required each time there is significant evolution of H_2 during degassing or of CO during decarburisation as explosive gas mixtures and ignition temperatures may occur.
- Cleaning of any pump system is only necessary in cases where no bag filter is installed.
- Dust handling by collection or pneumatic transport is necessary for all pump systems. In addition to this the very costly sludge handling must be taken care of in all wet systems.
- Water treatment for cooling, filtering, CO removal and oxidation prevention is required for all SVP systems. In MVP systems the total water throughput is so low that it can be of once-through type.
- Steam handling requires either storage, overheating and insulation of the steam reservoir in case of excess steam formation in integrated steel plants or the generation of steam in a fuelled boiler that is kept at a low fire during stand-by.

3 Energy consumption

A short-sighted consideration of the costs of investment and operating as well as for

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safety, health and environmental aspects has led to the erroneous development of vacuum plants that operate with SVP since steam has been considered to be a very cheap source of energy.

Large air leaks, protective gas flows and excessive pressure drops were therefore accepted and led to the design of huge steam ejectors demanding extremely high energy consumption. Efforts to reduce such costs were neglected. As a result vacuum plants using SVPs became significant energy-wasting devices for the following reasons:

- The energy efficiency of any SVP system is poor. The consumption of steam is nearly constant and high from 100 hPa down to the end of treatment when the gas density is very low. In contrast in MVP systems the energy demand shows a peak of about 2/3 of the installed motor power when the pressure reaches 60–30 hPa but falls continuously to 1/3 of the installed motor power towards the end of the treatment cycle.
- Pump-down control becomes energy consuming when it is carried out using inert gas injection or re-circulated off-gas. MVP systems perform pump down control to as large extent [6–8] by frequency control i.e. by reducing the energy consumption.
- The vacuum is killed after every treatment cycle and must be re-established for a new cycle when a main isolation valve between the SVP and the reaction vessel is not usually installed. In fact, reliable raw gas isolation valves are needed that withstand the high gas temperatures and erosion by high-speed dust particles without creating a high pressure drop [9]. This permits a vacuum to be maintained in the bag filter between treatment cycles and a very rapid drop in vessel pressure down to 400 to 700 hPa when opening this main shut-off valve. Owing to the lack of filter volume any energy saving by a pre-evacuated volume is restricted in SVP systems.
- Conveying of hot dust-laden gases requires additional energy. About 10% more steam is required when the off-gases are at 250 °C instead of 20 °C [10].
- Large air leaks have been tolerated in SVP systems when compensated by additional suction capacity [3]. However, reducing air leaks is cheaper than installing over-capacity.
- Protective gases are admitted in large amounts. As an example a nitrogen flow of up to 150 Sm^3/h is needed to protect an oxygen lance in stand-by position against clogging [3]. This requires additional suction capacity of about 230 000 m^3/h at 0.67 hPa and the associated investment costing about €1.4 M in the case of a MVP, as well as ~€0.25 M running cost a year at a production rate of 1.5 Mt/y [1,2].
- This money could be better used to modify the lance design or adapt the process features to avoid the need for this large amount of protective gas [9].
- Air leaks, protective gas flows and argon for metallurgical purpose are listed in Table 2 for the various processes.
- Pressure losses requiring an additional suction capacity of >40% can frequently be observed on large heats [11]. As an example heats >300 t with 1200 kg/h DAE (Dry Air Equivalent) SVP capacity at 0.67 hPa [3] would require a first stage ejector port of 2.1 m diameter designed for a gas velocity of about 100 m/s.

Comparable MVP systems with 1 M m^3/h capacity aim at half this gas velocity in order to limit the pressure losses and therefore might require a suction pipe diameter of 3 m, a low number of pipe bows and a filter surface of 1600–2000 m^2.

However, due to space limitations the suction ports of VD tanks or RH vessels rarely exceed 1.8 m in diameter.

The consequences of pressure losses on the effective suction capacity prevailing at the metallurgical reaction vessel are demonstrated in Figure 4 for the two considered pump systems each being proposed for a 300 t RHO plant.

In this figure a SVP with a mass flow capacity of 1000 kg/h at the design pressure of 0.67 hPa and a MVP with 80% of this capacity as determined at the pump inlet are shown.

For both systems the pressure drop is based upon a suction pipe diameter of 1.8 m, 25 m length with 8 bows of 90° as well as a

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Table 2. Sources of leaks and protective gases for various vacuum plants and processes (• light, •• medium, • • •) (VID- Vacuum Induction Degassing, VCD –Vacuum Carbon Deoxidation, VOD[C] – Vacuum Oxygen Decarburisation [in Converter], VIT – Vacuum Ingot teeming, VD-OB – Vacuum Degassing assisted by Oxygen Blowing, RH – Vacuum Circulation Process, RHO – RH assisted by Oxygen).

Process and reaction vessel	VID furnace	VD in ladle	VD in tank	VODC converter	VIT tank	VD-OB/ VOD tank	RH vessel	RHO vessel
Sources of leaks								
- Main vessel sealing	•	• • •	••	• • •	••	••		
- Off-gas swivel joint	•						••	••
- Snorkel connection							•	•
- Alloying chute	•			• • •	••	• • •	• • •	• • •
- Lance/burner port				• • •		• • •	••	• • •
- Sampling port	•							
- Observation port	•	•	•		•		•	•
Observed leaks in kg/h	0.4	30–50	5–25	30–60	1–5	20–50	40–50	60–90
Target leaks in kg/h	0.1	<30	<10	<30	<5	<20	<40	<60
Protective gases								
- Blowing lance/Burner				•		•	••	• • •
- Observation port	•	•	•		••			•
Observed gas rates in Sm^3/h	6–10	6–10	6–10	10–20	10–30	20–60	10–20	>150
Target gas rates in Sm^3/h	<10	<10	<10	<10	10–30	<10	<10	<100
Purging gas								
– for melt stirring in Litre/min/t	<0.5	1–3	2–5	5–6	–	5–6		
– for melt lifting in Litre/min/t					–		6–8	6–8

filter surface of 1800 m^2. In this example the filter is responsible for 1/3 of the pressure losses.

Owing to the square influence of the gas velocity [9] it turns out that the higher suction capacity as determined at the SVP pump set disappears at the reaction vessel against a MVP with a mass flow design capacity of 80% of that of the SVP in the operational pressure ranges. This figure also demonstrates that one cannot take profit of any overcapacity if nothing is done to reduce the pressure losses further.

3.1 Suction capacities

SVP systems are focused on heavier melt weights of up to 350 t. Their suction capacities are seldom <100 kg/h and in large RHO plants may reach 1200 kg/h DAE at 0.67 hPa [3] and 2200 kg/h at 2 hPa. This high figure of mass flow is mathematically equal to 1.5 Mm^3/h but does not mean at all that such high volume flows are required in MVP-systems.

MVP pumps are mainly used for the smaller heats of 10–80 t. Many MVP systems have been operating successfully for decades at a level of 25–40 kg/h DAE suction capacity at 0.67 hPa for melts in the range of 25–50 t. Their use has been extended up to 230 t heats with 650 kg/h at 0.67 hPa and 1750 kg/h at 2 hPa [11], both figures are as calculated at the pump set inlet. The extension of the use of MVP sets for large heat weights shows no limit as additional pump sets can be added.

MVP systems are volume conveyors ie they are independent of the gas density, whereas SVP systems are mainly mass conveyors but are **not** independent of the gas density.

In fact for the SVP-systems a total mass air equivalent (TMAE) must be determined [3, 10] that can be up to 2.7 times higher than the Dry Air Equivalent (DAE) depending upon the off-gas composition. (The TMAE formula contains correction factors for the different gases against air. This factor is 5 for the light H_2-gas and 0.87 for the

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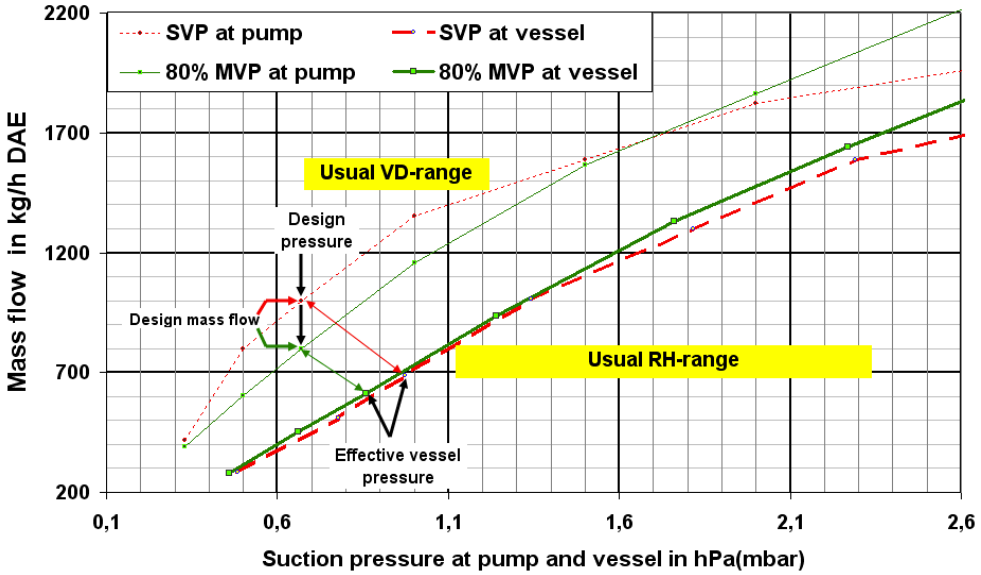


Fig. 4. Mass flow in SVP and MVP systems both with dust filters for a 300 t RHO plant.
Fig. 4. Flux massique pour un système d'éjecteurs et de pompe mécaniques les deux avec filtre à poussière pour une installation RHO de 300 t.

Table 3. Calculation of required MVP volume flow from SVP mass flow (300 t).

Process	VD	RH	RHO
Main target	Degassing	Degassing	Decarburisation
Cycle time	30 min	25 min	20 min
End pressure	0.67 hPa	1 hPa	2 hPa
SVP mass flow [3]	700 kg/h	750 kg/h	1000 kg/h
TMAE correction coefficient	1.75 (57%)	1.5 (67%)	1.25 (80%)
MVP corrected mass flow	400 kg/h	500 kg/h	800 kg/h
MVP volume flow at the above operational end pressures	503 000 m^3/h	420 000 m^3/h	335 000 m^3/h
MVP volume flow at the uniform design pressure 0.67 hPa	503 000 m^3/h	630 000 m^3/h	1 008 000 m^3/h

heavier gases Ar and CO_2 [3,10]). Therefore for many cases of equal melt weights the required mass flow capacity of any SVP system is higher than for MVP systems [12].

Examples of volume flow for 300 t plants equipped with MVP are given in Table 3.

In this table the SVP mass flow is TMAE-corrected, i.e. gas composition corrected, and then converted into a mass flow need for MVP systems and several processes. The TMAE factors are rather high in VD processes when a lot of hydrogen develops at a medium argon stirring rate. This is different in RH processes with a high argon flow and a large CO development for which the TMAE correction coefficient becomes smaller.

Other reasons for the difference in pump capacity between the systems have been explained in the past [4,5], and they are mainly based on:

- the higher gas temperature admitted at the pump inlet [10];
- the higher dust load;
- a reserve for ejector clogging;
- a reserve for wear of steam nozzles and ejectors;
- a reserve for weak conditions of steam and water;
- the typical pump characteristics as shown in Table 4.

In fact, Figure 4 shows more than the effect of pressure drop. It shows the essential

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Table 4. Variation of mass flow in kg/h DAE over pressure for SVP and MVP.

Pressure measured at the vacuum pump	0.33 hPa	0.67 hPa	2 hPa	100 hPa
SVP as reference	420	**1000**	1820	9000
MVP with SVP-equal mass flow at 0.67 hPa	490	**1000**	2330	19 000
MVP after TMAE correction	390	800	1860	15 200

difference in pump characteristics of the two systems as one can also see in Table 4.

While the suction capacity is equal at a given design point (0.67 hPa) the MVP systems have a much higher capacity in volume flow and in mass flow at higher vacuum pressures.

The usual practice in many SVP systems, designed for 0.67 hPa, is to operate at about 2 hPa final pump pressure. This arises due to significant losses of pump performance caused by ejector clogging and steam nozzle wear.

Accepting this situation, which is not detrimental to the metallurgical performances in vacuum processes using high argon flows eg 5–8 L/min/t, one could use MVP systems with much lower 0.67 hPa capacities than those of the SVP systems. As Figure 4 shows for the two systems with dust abatement the performance of a MVP with less capacity at the design pressure 0.67 hPa is close to that of the SVP system at low pressure and superior at pressures >2 hPa.

Neither Figure 4 nor the abovementioned Tables 3 and 4 however, show the real need of suction capacity. In fact out of 1820 kg/h at 2 hPa (resulting from a SVP design for 1000 kg/h at 0.67 hPa) for a RH process only less than 5% are needed to remove the metallurgical process gases H_2 + N_2 + CO, ~30% are needed for the permanent gas loads of Ar, N_2 and air, ~15% to compensate pressure losses, while the remainder of ~50% is a reserve for other losses due to ejector clogging, nozzle wear and bad fluid conditions.

If final treatment pressures lower than 2 hPa are aimed at, this reserve may drop to 20% but is nil at any pressure in case of a MVP. This confirms the previous statements [4, 5, 12] that a MVP needs much less suction capacity than a SVP for the same operational and metallurgical results.

4 Conclusions

How to evaluate the need for a pump capacity?

1. Reduce the permanent gas loads of the vacuum plant that are of no metallurgical use such as air leaks and nitrogen as protective gas.
2. Check the mean gas composition during the vacuum process.
3. Calculate the total mass air equivalent (TMAE) on the basis of this gas composition.
4. Design suitable dust abatement and duct connection aiming at low pressure losses.
5. Calculate the real suction capacity need assuming constant or unchanged minimum pump performances during the whole lifetime of the pump set.
6. Apply the TMAE factor when opting for SVP, disregard it in case of a MVP.
7. Select a reasonable vacuum pressure to be reached at the end of the vacuum treatment cycle.
8. Convert the resulting mass flow to a volume flow for a MVP.
9. Make your choice of SVP or MVP including all aspects like energy and fluid consumption, wear, maintenance and cleaning, redundancy, availability, emissions, dust and sludge handling climatic conditions, safety and health standards.
10. For MVP select the next highest pump capacity of skids or lines offered on the market.
11. Select the MVP system with the highest flexibility in terms of quick response time to gas load changes, pressure control, redundancy, compliance with ATEX requirements, rapid exchangeability of individual pumps and upgrading possibilities [6–8].

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