Vacuum treatments for hydrogen removal in 140 ton ladle for big ingots casting

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Hydrogen removal can be accomplished via different steelmaking routes (VOD, ASEA, RH). Focus was given on the first two technologies. As main differences between the systems based on a (multi)-plug equipped ladle, in VOD the vacuum chamber is obtained by coupling a roof with a tank, in ASEA plant –where electromagnetic melt stirring is also exploited - coupling occurs directly with the ladle, leading often to a non perfect sealing. Moreover, VOD plant is able to perform under vacuum steel degassing treatment at pressure values lower than usually reached in ASEA plant, and is also equipped with a oxygen lance allowing to produce stainless steels with very low carbon and nitrogen content. The industrial need of achieving very low hydrogen contents for big ingots casting with an acceptable costs/benefits ratio called for a comparison between performances of different vacuum treatments strategies. A CSM numerical degassing model was applied to 140 ton ladle conditions either after ASEA or VOD treatment.

KEYWORDS:
acciaio, degasaggio sotto vuoto, affinazione acciaio, deidrogenazione, lingotti

INTRODUCTION

Hydrogen removal can be accomplished under vacuum via different steelmaking routes , e.g., VOD, ASEA, RH. Within the VOD technology, the vacuum chamber is obtained by coupling a roof with a tank. On the other hand, in ASEA plant –where electromagnetic melt stirring is also exploited – such a coupling occurs directly with the ladle, leading often to a non perfect sealing. The most relevant capability of a VOD plant for dehydrogenation treatments is the achievement of a stronger vacuum level than usually reached in ASEA plant. Another is the lower risk to have damages due to splashing phenomena respect to ASEA plant. Due to these features, VOD (VD) plant technology is used by many ingot producers to point toward very low hydrogen contents in melt, with shorter vacuum treatment than ASEA plant.
The industrial need of achieving in TKAST very low hydrogen contents (lower than 1 ppm) for big ingots casting with an acceptable overall costs/benefits ratio called for a comparison between performances of different vacuum treatments strategies. A CSM numerical degassing model was applied to 140 ton ladle conditions either after ASEA or VOD treatment. The benefits of a VOD treatment are highlighted, together with indications on the best working conditions, supported by encouraging experimental results.

ASEA AND VOD DEGASSING

The hydrogen reaction is controlled by liquid phase mass transfer of hydrogen. For non recirculating systems the reactions increase with argon stirring in a complex manner (schematic in figure 1 [1]). Due to the bubbles expansion, which occurs in function of pressure and liquid height, rate equations are complex [2].

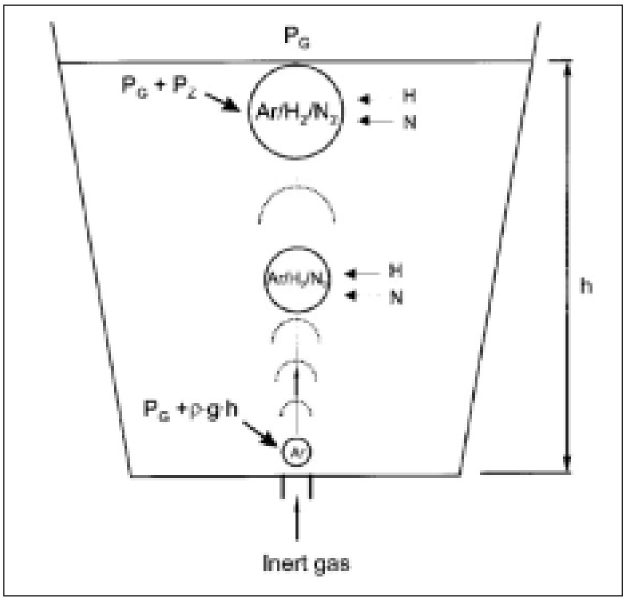

FIG. 1 ***Schematic of melt degassing phenomenon driven by inert gas bubbling [1].***

Schema del fenomeno di degasaggio di un bagno metallico grazie al soffiaggio di bolle di gas inerte [1].

Degassing reaction follows the relationship:

$$-\frac{dX}{dt} = \frac{k_x A}{V}(X - X_E) \tag{1}$$

Here X is the concentration of the element undergoing on degassing up to the equilibrium value X_E, V the steel volume, k_x the mass transfer coefficient and A the area exchange (=effective reaction surface) which under vacuum depends on pressure and bath height.

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As a result, after integrating (1), one obtains for hydrogen:

$$\ln\frac{[H]_f-[H]_e}{[H]_i-[H]_e}=-kt \qquad (2)$$

where [H] is the hydrogen concentration, the labels f, i, e refers respectively to final, initial and 'ideal' (as state by equilibrium conditions) concentration. For 'strong' degassing (below 10 torr) [H]e can be neglected with respect to the other terms, so the rate equation becomes:

$$\ln\frac{[H]_f}{[H]_i}=-kt \qquad (3)$$

The CSM model was based on such a relationship, integrated by a bubble size estimation in function of flow rate [3,4]. The model was applied to ladle treatment in TKAST ASEA and VOD conditions. The single-straight type ASEA electromagnetic stirrer allows clockwise melt flow, from wall to surface and again toward the bottom, and the melt velocity imposed decays rapidly from wall to center [3].

The 140 ton VOD ladle has a diameter/height ratio equal to 1, and two eccentric plugs, both in a half side of the bottom plane, one at half radius and the second at 800 mm from the first.

RESULTS AND DISCUSSION

A CSM numerical model, based on equations (1÷3) were applied to TKAST ASEA and VOD conditions, accounting for the ladle steel volume, the bubble area arising from the flow rate injected and the mass transfer coefficient k dependent on steel velocity [2]. In this way, the overall rate equation can be written [1]:

$$-\frac{d[H]_L}{dt}=\frac{Q_M}{W}([H]_L-[H]_e) \qquad (4)$$

where Q_M is the melt recirculation rate, related to steel velocity [5].

The recirculation rates needed were taken from modelling calculations. To achieve the recirculation rate term:

- numerical simulations, based on a Computational Fluid-dynamics model accounting for electromagnetic forces, were performed for ASEA conditions (see figure 2),
- physical modelling simulation were performed to simulate VOD conditions. Here, a 1:4 water model scale was built at CSM labs (figure 3). Flow rates (plugs, lance) were scaled according to the Similarity theory (keeping the same Froude's number between model and plant [4]).

The reason of using different modelling strategies for the different technologies is the following.

Recirculation rate (expressed in m^3/s), relevant parameter in (4), represents the liquid flow rate in the ladle 'batch' volume. Moreover, recirculation rate is equal to ladle volume divided by the 'homogenisation time' (defined as the time needed to achieve perfect homogenisation throughout all the liquid volume with respect to a well defined quantity – e.g., temperature, alloying elements concentration). Therefore, a way to achieve recirculation rate values is to measure melt homogenisation times. In the VOD frame, it is more reliable to achieve this information from physical model, therefore, the reduced scale VOD water model was set up.

On the other hand, electromagnetic forces cannot be simulated in a water modelling frame, and for ASEA the recirculation rate values were derived directly from the liquid velocity values after numerical calculations.

To assess mixing times and in turn take information on the recirculation rates for the VOD dehydrogenation model, a conductivity technique was used. A salt solution is injected into the liquid and a probe connected to a conducimeter allows the visualisation of the conductivity signal.

When an asymptotic value is achieved, complete mixing was attained in the liquid.

For ASEA calculations, different flow rates were simulated, together with cases where induction stirring effect was in the same direction or countercurrent with respect to the ascending gas. The results are summarised in figure 4. Start hydrogen concentration was 3.5 ppm. As a result, on one hand the increase of flow rate proved to favour more efficient degassing, on

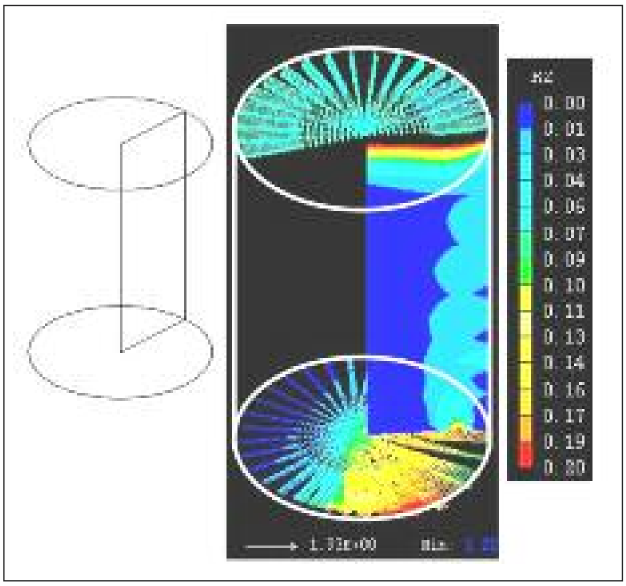

FIG. 2 ***Example of result with CSM fluid-dynamics modeling of flow in ASEA ladle with electromagnetic forces and gas stirring. Coloured map in the plane highlighted passing per a plug represents gas volume fraction. Velocity vectors (unit in m/s).***

Esempio di risultati con modello fluidodinamico del moto dell'acciaio nella siviera ASEA sotto l'azione dell'induzione elettromagnetica e del gas di stirring. Frazione in volume di gas (mappa) e velocità (in m/s) nel piano passante per un setto.

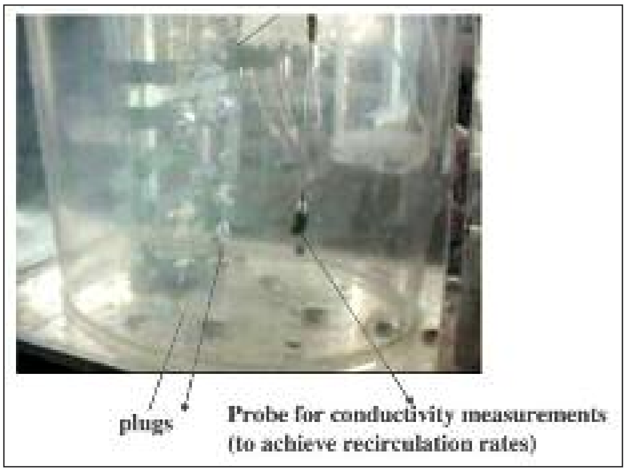

FIG. 3 ***Image of the CSM water scale model of TKAST VOD ladle system.***

Modello ad acqua in scala della siviera VOD di TKAST, presso i laboratori CSM.

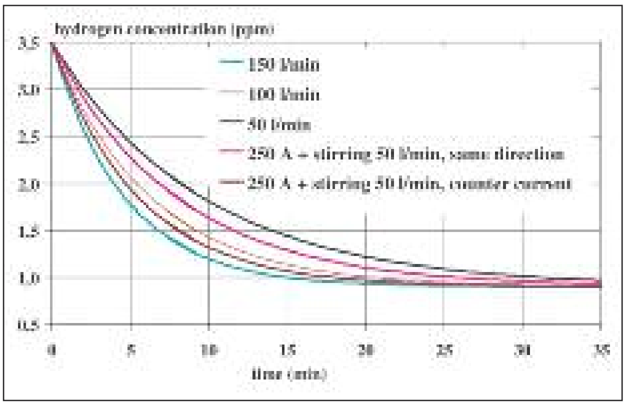

FIG. 4 ***Results of the CSM dehydrogenation numerical model to ASEA TKAST conditions. Hydrogen content in melt vs treatment time for different stirring conditions (see legenda).***

Risultati dell'applicazione del modello numerico di deidrogenazione CSM nelle condizioni operative ASEA in TKAST. Contenuto di idrogeno nell'acciaio in funzione del tempo di trattamento per differenti condizioni di agitazione (vedi legenda).

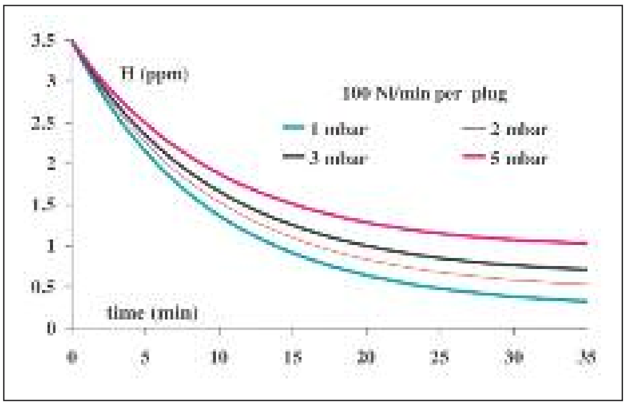

FIG. 5 ***Results of the CSM dehydrogenation numerical model to VOD TKAST conditions. Hydrogen content in melt vs treatment time for different vacuum levels. Gas flow rate 100 l/min per plug.***

Risultati dell'applicazione del modello numerico di deidrogenazione CSM nelle condizioni operative VOD in TKAST. Contenuto di idrogeno nell'acciaio in funzione del tempo di trattamento per diverse condizioni di vuoto (vedi legenda). Portata gassosa per setto: 100 l/min.

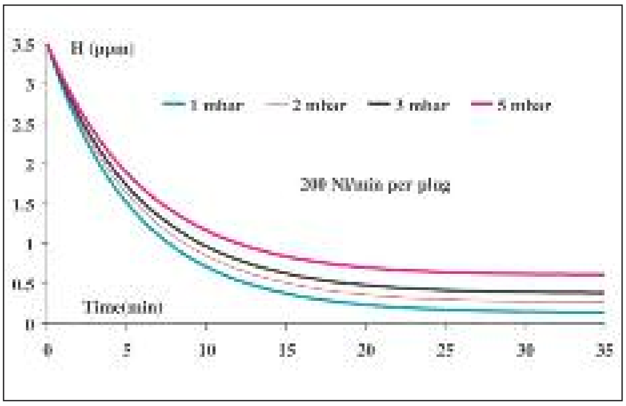

Fig. 6 ***Results of the CSM dehydrogenation numerical model to VOD TKAST conditions. Hydrogen content in melt vs treatment time for different vacuum levels. Gas flow rate 200 l/min per plug.***

Risultati dell'applicazione del modello numerico di deidrogenazione CSM nelle condizioni operative VOD in TKAST. Contenuto di idrogeno nell'acciaio in funzione del tempo di trattamento per diverse condizioni di vuoto (vedi legenda). Portata gassosa per setto: 200 l/min.

the other hand the adequate managing of induction stirring compensated for a lower flow rate, useful to reduce risks of splashing in ASEA layouts. The better condition occurs when induction and gas stirring are counter-current (the residence time for bubbles in melt is longer, and the higher turbulence can further break gas flow into bubbles enhancing the exchange area for dehydrogenation).

A constant pressure value of 2 mbar was used in the calculations.

For VOD calculations, the dehydrogenation trend in function of the plug gas flow rates (100 e 200 Nl/min) is shown in figure 5 and 6. The stronger the vacuum, the lower the equilibrium hydrogen (asymptotic value). The higher the flow rate, the more efficient is the treatment, due to the enhanced exchange area between bubbles and dissolved hydrogen.

The model sensitivity to flow rate proved to be in agreement with other similar validated tank degassing models results [2]. The effect of a lower pressure is much more significant than that of the gas flow rate, even though as soon very low pressure values are approached (<10 mbar), the dehydrogenation rate increase is lower.

By comparing figures 4, 5 and 6, the stronger VOD efficiency with respect to ASEA operations is shown. Taking as a reference a hydrogen target content of 1 ppm, one can see that the difference between the most efficient ASEA and VOD performances can also exceed 5 min.

This result shows how equilibrium aspects (effect of pressure, number of bubbles) are of prevailing importance in dehydrogenation process with respect to mixing phenomena in the melt. As a matter of fact, ASEA dehydrogenation performances are less efficient in spite of the better mixing behaviour of ASEA the electromagnetic stirred melt.

This can be shown in figure 7, where in a literature [7] diagram correlating power transferred to melt by different stirring system, the working point corresponding to our two cases were derived [8, 9] and evidenced.

Besides, the fact that dehydrogenation does not increase automatically with gas stirring is explained by the fact that in gas stirred systems under vacuum, the gas expansion is mainly concentrated close to the surface. It was estimated that 50% of the expansion occurs within a distance from the ladle surface equal to 20% of the total bath height [10].

As a result, when exceeding the flow rate values needed for a reasonable rapid mixing (around 100 Nl/min) most part of the further flow rate is spent for energy dissipation at the surface, with risks of splashing due to the close coupling roof-ladle, and is not fully available to enhance melt recirculating rate and bath mixing.

Summarising, the most powerful driving force for efficient hydrogenation process proved to be the dissolved hydrogen equilibrium shift towards stronger vacuum levels.

The further advantage of VOD layout (higher roof makes harmless splashing occurrence) allows to enhance the process by injecting higher gas flow rate in the melt. Gas stirring policy can be further enhanced also with suitable flow rate management in case of multi-plug ladle.

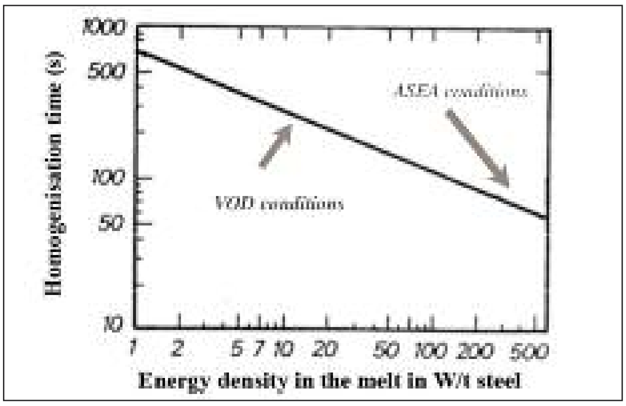

FIG. 7 ***Diagram correlating specific power transferred to a melt with stirring systems (electromagnetic, gas) and bath homogenisation time [7]. The working points (calculated from [8] and [9]) corresponding to the conditions of figures 5, 6 and 7 are highlighted.***

Diagramma che correla la potenza specifica ceduta al bagno metallico mediante diversi sistemi di agitazione (elettrromagnetica, gas) e il tempo di omogeneizzazione del bagno metallico [7]. I punti di lavoro sono calcolati da [8] e [9] e corrispondono alle condizioni delle figure 5, 6 e 7.

Based on these aspects, VOD-based steelmaking route was used in TKAST, for forging steel fabrication, to obtain hydrogen values lower than 1 ppm for bottom pouring ingots, avoiding expensive anti-flakes treatments after forging.

Table 1 shows the results obtained after 30 minutes of vacuum treatment in 140 ton ladles performed in both TKAST VOD and ASEA plants. The average lower content (-25%) achieved after VOD treatment, supports the model indications. Here, hydrogen measurements were performed in both cases by the same Hydris device just at the end of vacuum treatment. This means that results are comparable, and the differences are not dependent on instrumental accuracy. Hydris devices are widely used for hydrogen measurement inside ladles, and their accuracy is usually acceptable for this kind of production.

Moreover, the verified model suitability allowed more in general to get a tool for driving the dehydrogenation strategy, by optimising treatments times (and in turn, costs) in function of the metallurgical targets in degassing operations for the steel being produced.

Heat n.	Hydrogen content (ppm) after treatment	
	VOD	ASEA
1	0.8	1.1
2	0.9	1.2
3	0.8	1.0
4	0.7	1.2
5	0.9	1.0
6	0.8	1.1

TAB. 1 ***Hydrogen content in the steel after 30 minutes of vacuum treatment performed in 140 ton ladle (TKAST VOD and ASEA plants).***

Contenuto di idrogeno nell'acciaio dopo 30 minuti di trattamento sotto vuoto attraverso VOD e ASEA nella siviera TKAST da 140 ton.

CONCLUSIONS

With the aim of achieving very low hydrogen contents for big ingots casting with an acceptable costs/benefits ratio, a CSM validated model was used to compare the dehydrogenation performance at the TKAST 140 ton ladle conditions either after ASEA or VOD treatment.

The most relevant results were the following:

- ASEA treatment is efficient when coupling purging to electromagnetic stirring with induced flow counter current with respect to the gas plume from the plug. Increasing the gas flow rate per plug is risky, due to the gas expansion, mainly concentrated close to the surface, inducing risks of splashing due to the close coupling roof-ladle;
- VOD operations are more effective because of the strongest vacuum levels achievable. As a result, the equilibrium gas partial pressure is lower than in ASEA operation, and dehydrogenation can continue up to very low level;
- a further advantage of dehydrogenation through VOD operations is related to the VOD layout. The higher roof makes harmless splashing occurrence, so an increased flow rate can be used to enhance in the melt presence of bubbles where dissolved hydrogen diffusion occurs. Gas stirring policy can be further enhanced with suitable flow rate management in case of multi-plug ladle performed by the aid of CSM validated model indications.

Based on these aspects, even if ASEA based route should be preferable for logistic reasons, VOD-based steelmaking route was used in TKAST, for forging steel fabrication, to obtain hydrogen values lower than 1 ppm for bottom pouring ingots, avoiding expensive anti-flakes treatments after forging.

Moreover, the verified model suitability allowed more in general to get a tool for driving the dehydrogenation strategy, by optimising treatments times (and in turn, costs) in function of the metallurgical targets in degassing operations for the steel being produced.

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Abstract

Deidrogenazione sotto vuoto in siviera da 140 ton per il colaggio di grandi lingotti

Parole chiave: steel, steelmaking, dehydrogenation, ingots, vacuum steel degassin

La deidrogenazione può essere effettuata secondo differenti cicli d'acciaieria (che prevedono VOD, ASEA, RH). Questo studio è incentrato sui primi due. La differenza sostanziale fra questi sistemi è che nel VOD la camera di vuoto è ottenuta con un reattore chiuso da una volta, nell'impianto ASEA, dove il metallo liquido è anche agitato elettromagneticamente, è accoppiata direttamente con la siviera, non sempre a perfetta tenuta. Inoltre, l'impianto VOD permette di effettuare trattamenti sotto vuoto più spinto rispetto all'ASEA, ed è anche dotato di una lancia ad ossigeno che permette la produzione di acciaio inossidabile con contenuto bassissimo di carbonio e azoto.

La necessità di ottenere una deidrogenazione spinta nel colaggio di lingotti da forgia in quadro di accettabile rapporto costi/benefici ha portato a confrontare l'efficacia di differenti trattamenti sottovuoto nelle condizioni di TKAST. Per l'occorrenza, è stato applicato un modello di degasaggio CSM alle condizioni di lavoro negli impianti ASEA e VOD.

I risultati più rilevanti sono stati i seguenti:

- il trattamento ASEA è efficiente quando si effettuano nello stesso tempo stirring con gas ed elettromagnetico, imponendo all'acciaio un moto in senso opposto a quello del flusso di gas. Un aumento della portata gassosa è rischioso a causa dell'espansione del gas sotto vuoto, che avviene principalmente presso l'interfaccia metallo-scoria, con pericolo di proiezioni di fluido (acciaio e scoria) verso la volta;
- il fatto che il trattamento VOD dia luogo a deidrogenazione più efficiente rispetto a quella che si ha in ASEA, nonostante l'agitazione elettromagnetica sia più efficace, indica come il fenomeno sia legato più alla chimica del processo che alla fluidodinamica dell'acciaio liquido;
- il trattamento in VOD è più efficace per i livelli più spinti di vuoto ottenibili. La pressione parziale del gas in condizioni di equilibrio è minore che nel trattamento ASEA, e la deidrogenazione può andare avanti sino a livelli molto spinti. Nel nostro caso, l'obiettivo di un contenuto di idrogeno di 1 ppm è ottenuto circa 5 minuti prima rispetto al processo ASEA;
- un ulteriore vantaggio della deidrogenazione in VOD piuttosto che in ASEA è di tipo impiantistico. La maggiore altezza della volta in VOD di fatto neutralizza i rischi di proiezioni di fluido verso l'alto. Quindi possono essere usate maggiori portate di argon, il che vuol dire un maggior numero di bolle nel liquido disponibili per la diffusione dell'idrogeno. La strategia di soffiaggio di gas inerte può essere ulteriormente migliorata con la gestione della portata in una siviera a più setti porosi basata sulle indicazioni derivanti dal modello CSM.

Sulla base di queste considerazioni, malgrado il ciclo ASEA sia preferibile per motivi logistici, è stato seguito un ciclo di fabbricazione basato sulla deidrogenazione in VOD per il colaggio in TKAST di grandi lingotti. In questo modo, sono stati ottenuti bassi valori di idrogeno, inferiori ad 1 ppm, evitando successivi costosi trattamenti 'anti-fiocco' dopo la forgiatura. In più, il modello si è dimostrato un strumento affidabile ed utile a calibrare, più in generale, tempi e prestazioni legate ai trattamenti di degasaggio fornendo un contributo importante al miglioramento della produttività.