LATEST DESIGN ASPECTS OF THE AOD STEELMAKING CONVERTER[1]

G. Staudinger[2]
S. Dimitrov[2]

Abstract
This paper shows some new design features and technological results of a modern, state-of-the-art AOD-converter. Based on the experience of SIEMENS-VAI, substantial improvements with respect to the metallurgical performance during the decarburization and reduction-phase can be made through the application of a modified shape of the AOD vessel shell in comparison to the classic design. Consequently, an increase in the lining life-time of at least 10% can be achieved. Additional advantages with regards to manufacturing, operation and maintenance/relining of the AOD vessel are possible. Further improvements of adjacent equipment like suspension systems, media gas supply, etc. are shown in order to increase safety and availability of equipment as well as productivity. Hence, there is a large variety of possibilities to meet the requirements of the individual customers demands, e.g. to find an optimum solution between investment and production costs and the return of investment.
Key words Converter; Stainless steelmaking; AOD-process.

ASPECTOS DE DESIGN ATUAIS DO CONVERTEDOR AOD

Resumo
Este trabalho apresenta novas características de design e resultados tecnológicos de um moderno Convertedor AOD. Baseado na experiência da SIEMENS VAI, melhorias substanciais respeitando-se a performance metalúrgica durante a decarburização e fase de redução podem ser realizadas através da aplicação de uma forma modificada da carcaça do vaso AOD em comparação ao design clássico. Consequentemente, um aumento no tempo de vida de no mínimo 10% poderá ser alcançado. Vantagens adicionais em relação à fabricação, operação e manutenção do vaso AOD são possibilitadas. Melhorias adicionais do equipamento adjacente tais como sistemas de suspensão, equipamento de fornecimento de gás, etc., são mostradas com o objetivo de aumentar a segurança e disponibilidade do equipamento, assim como sua produtividade. Podemos concluir que existe uma grande variedade de possibilidades para se atingir as especificações das demandas individuais do cliente, como por exemplo encontrar uma solução ótima entre investimento, custos de produção e retorno de investimento.
Palavras-chave: Convertedor; Aciaria de inoxidável; Processo AOD.

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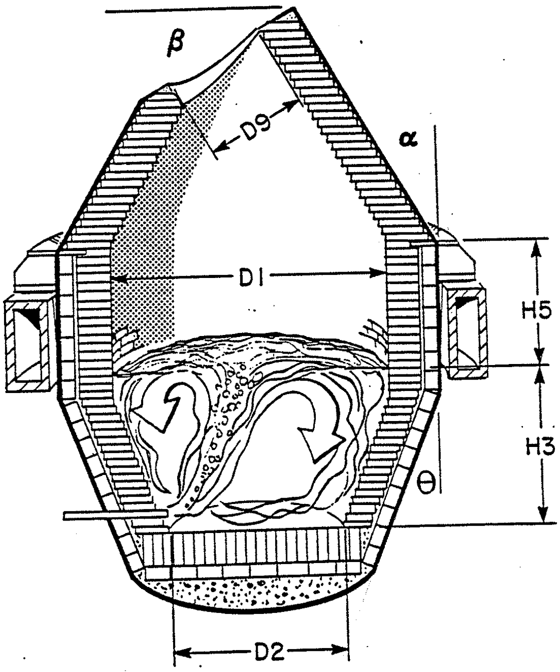
[2] *Siemens VAI Metals Technologies GmbH & Co*

INTRODUCTION

Since the year 2000, an increased demand of stainless steel production has been observed worldwide. In the nineties, a typical stainless steel plant had an annual capacity of 0.5 mt/y based on an 80 t to 100 t heat size. In the year 2000, the nominal heat size increased to 120 t and 150 t, achieving 0.7-0.8 mt/y (Outokumpu Tornio, AOD route at ALZ Genk). Recently, because of further increased demand – especially in China – and the necessity for reduced production costs, the capacity of stainless steelmaking plants was increased up to 1 mt/y based on a 180 t heat size (TISCO, China).
Siemens VAI, as a leading supplier for the steelmaking and particularly for the stainless steelmaking industry, introduced several improve-ments for equipment as well as process technology and was honored with major important projects (CARINOX/Arcelor, ZPSS/Posco, TISCO/China, LISCO/ Taiwan).
This paper shows some new design features and technological results of a modern, state-of-the-art AOD converter.

HISTORICAL DEVELOPMENT OF DESIGN CRITERIA FOR AOD VESSEL SHAPE

The classical AOD vessel shape and design parameters in accordance to the original patents applied for nearly all known vessels until approximately 2002 are shown in Figure 1.
The main objective with this arrangement is the optimization of the hydrodynamic flow and bath mixing. The process gas blown via submerged side-tuyeres into the liquid steel (inert gas N_2/Ar or oxygen + inert gas mixture) creates two base streams (left and right-hand directions) and improves the chemical reaction rate during decarburization, during the reduction steps and afterwards, and also improves the assimilation of added materials.



Main design parameters (original AOD shape)

- Ratio $\varepsilon = \frac{D_1}{H_3}$ of approx. 2 (eq. 1)

D1: Bath diameter at slag/metal surface

H3: Bath height (depth) at slag/metal surface

- Same height of upper & lower cone and barrel (cylindrical part)

α = Θ = approx. 30 °

β = approx. 22.5 °

Figure 1: Classical AOD design

The next objective was to increase the duration of the vessel campaign in consideration of the higher wear rate of the side-tuyeres (approx. average of 0.3-0.5 mm/heat) and to achieve an approximately unique refractory wear at the end of the campaign.

In order to achieve this condition, the lining thickness in the area of tuyeres was increased by introducing a “knapsack” or “rucksack”, which was incorporated into the vessel shell by an extension of the vessel shell radius in the area of the tuyeres only.

Simulation of the Hydrodynamic Behavior of the Liquid Steel

Computational fluid dynamic (CFD) simulations were applied by Siemens VAI to attain more knowledge of the behavior of the steel bath. Figure 2 shows the results of such a numerical simulation. In this calculation, the behavior of the liquid steel during blowing of inert gas through 5 side tuyeres was simulated.

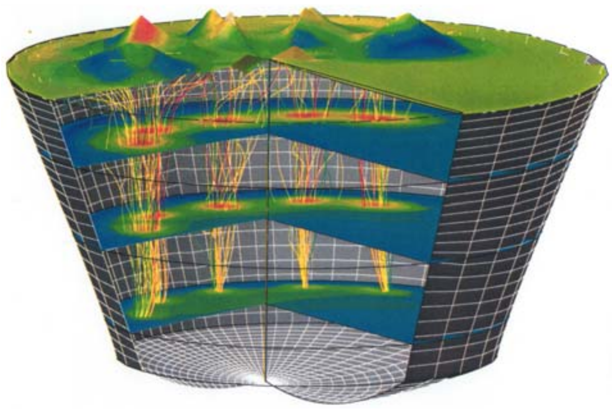


Figure 2: CFD analysis of the liquid steel bath during blowing of inert gas by submerged side tuyeres in AOD converter.

The highly nonlinear hydrodynamic formulation takes into account all important effects including free surface of the bath. The chemical and metallurgical reactions have not been taken into consideration. Hence, there is still a lot of additional research and development necessary in order to cover all basic effects of the real steelmaking process. However, in general, the results show the behavior very clearly and provide us with feedback for the optimization of converter design.

DECARBURIZATION IN AOD CONVERTER

The decarburization process by O_2 blowing through the submerged tuyeres can be explained schematically as follows:

A) Primary oxidization of Cr in the metal phase (premelt/steel) in the reaction area in the front of the submerged tuyeres:
$2[Cr]+3/2\{O_2\} \Rightarrow Cr_2O_3(S)$ (eq. 2)

B) Oxidization of C in the metal phase (premelt/steel) by partial reduction of primary formed Cr2O3 (as per A) in the transition reaction area between tuyeres and metal bath surface:
$3[C]+ Cr2O3(S) \Rightarrow 2[Cr]+3\{CO\}$ (eq. 3)

The net combined decarburization reaction by tuyeres only C = A+B can be expressed as follows:

C) $3[C]+ 3/2\{O2\} \Rightarrow 3\{CO\}$ e.g.

D) $[C]+ 1/2\{O2\} \Rightarrow \{CO\}$ (eq. 4)

In the case of oxygen blowing by top lance, in addition to the reactions A) and B), a direct oxidization of carbon by the oxygen jet near the metal surface (hot spot area) in accordance to reaction C) also takes place to some extent, which is supported by high temperatures of at least 2400°C in this area. And finally through the application of a top lance, a partial post combustion of CO within and above the slag layer in accordance with the reaction equation

$\{CO\}+1/2\{O_2\} \Rightarrow \{CO_2\}$ (e.q. 5)

takes place. The average post combustion degree within the AOD is usually limited to less than 7%.

The most relevant reaction step with regards to the decarburization process and efficiency in the AOD is reaction B), which can be improved within the existing conditions, limits and restrictions by higher process temperatures and lower CO partial pressure.

The actual CO partial pressure depends not only on the actual blown oxygen/inert gas ratio, but also on the actual total pressure in the gas bubble within the metal bath, which includes the pressure terms of steel layer, slag layer and the free space of the AOD vessel (last term is approx. 1 bar) above the gas bubble as well.

Hence at the same process gas ratio of O_2/inertgas, an additional improvement of the CRE in AOD converters can be achieved by decreasing the total pressure on the gas bubble as follows:

- improving bath mixing for improved kinetics
- reducing pressure in the free space above the bath, e.g. AOD converters with vacuum (applied in VD or VOD plants), which has already been implemented for special small sized AODs up to 60 t or
- reducing ferrostatic pressure by applying optimized vessel shape design with reduced bath height, which can be implemented for all AOD converter sizes (VAI's approach since 2003).

DESIGN FEATURES OF A MODERN AOD CONVERTER

With this knowledge, which is already successfully proven in practice, Siemens VAI has introduced several AOD converters with an increased ratio of bath diameter/bath depth (ε values in respect to Figure 1 in the range of 2.1-2.4 at new lining). Typical examples are ALZ/Belgium with ε = 2.4 and several new AOD converters with ε = 2.2, such as CARINOX/Belgium, ZPSS/China, TISCO SMP 4/China and LISCO/China.

However, due to boundary conditions (e.g. in case of revamping) or special requests of the customer, it is not always possible to design accordingly (e.g. BÖHLER/Austria ε = 1.65, TISCO SMP 3/China ε = 1.4).

Another approach to optimize the shape of the AOD is to reduce the increased wear in the intersection of the knapsack with the bottom cone section. In this area, the temperature is rather high and the wear of refractory is increased.

With these effects in mind, Siemens VAI has introduced an approximately axial-symmetrical vessel shell with asymmetrical lining in the area of the tuyeres.

With this design, the following the advantages can be achieved:

- Avoiding sensitive zone in the knapsack/cone area
- Increasing bath diameter and decrease of bath depth
- Easier preparation of the refractory lining of the vessel in the tuyere area
- Avoiding complicated welding of knapsack area, which decreases the cost of the vessel shell

The first big vessel came into operation in October 2005 in Carinox, Belgium with a heat size of 180 t. The results are excellent and the decarburization rate is most effective. A typical design of a 180 t converter is shown in Figure 3.

The achieved decarburization efficiency and other technological results are very satisfactory. For instance, the C content of 10 ppm before reduction can easily be achieved without an increase in consumption of Si_{red}. [C]+[N] < 80 ppm before tapping are also possible for 409 type steel grades.

Consequently a typical Siemens VAI converter shows the following main design features:

- nearly symmetric vessel shell
- asymmetric lining in the area of the tuyeres
- detachable top cone with simple and safe connection elements
- thin lining thickness in the top cone area
- long barrel section with short lower cone and spherical bottom
- easy detachable suspension system for changing the vessel within a short time
- horse-shoe type trunnion ring

Based on these characteristics, Siemens VAI has introduced a design tool based on a master design and best practice. By choosing a certain heat size and specific volume, the main dimension of the shell as well as lining and vessel shell thickness are determined automatically.

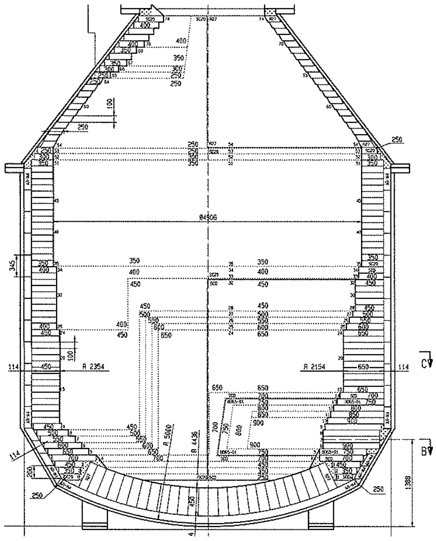


Figure 3: 180 t AOD converter

PLATE THICKNESS AND MATERIAL SELECTION

In principle, the thickness of vessel shell is defined using the same rules as for LD converters. In [1] these are summarized accordingly, with a result that the thickness is defined on best practice data collected from a worldwide survey applied by the AISE no. 32 subcommittee.
However, AOD converters have a thinner lining, a shorter life time and a higher liquid steel temperature (usually up to 1750 °C). Hence, the vessel shell is exposed to higher temperatures (400 to 500 °C). The top cone can be exposed to even higher temperature. Consequently, Siemens VAI uses high-temperature resistant pressure vessel material with increased creep resistances. The typical material used is of steel grade 16Mo3 or ASTM A 204 Gr.B.
The trunnion ring typically has a horse-shoe type design in order to change the vessel shell easily. With this open design, the deformation of the trunnion ring is rather large when compared to a closed type design. In order to keep this deformation, which is basically driven by temperature, to a minimum, trunnion rings have been water cooled for the last years. In the year 2000, Siemens VAI introduced uncooled horse-shoe type trunnion rings for various projects (80 t AOD at Arcelor Acesita/Brazil 120 t ALZ at ALZ Genk/Belgium and 150 t AOD at Outkumpu Tornio/Finland) based also on creep resistant 16Mo3 steel quality. The experience shows that the trunnion rings are in good condition and that water cooling is not necessary at all. This results in less maintenance, increased safety (no water) as well as less investment and operation costs.

SPOUT DESIGN

The spout is a very critical area of the AOD converter. The spout is exposed to high temperature, chemical and mechanical wear during charging, deslagging and tapping. Based on the experience of various AOD plants, Siemens VAI has continuously improved the spout design. The best solution is based on a refractory "monoblock" which is incorporated in the vessel shell (see Figure 4). There is normally no contact of liquid steel with the vessel shell or the lip ring during tapping and the "monoblock" optimally withstands temperature shocks and erosion. Consequently, the life time of the refractory is increased significantly.

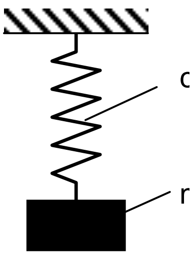
Figure 4: Spout design for "monoblock"

CONVERTER TILTING DRIVE

The Siemens VAI converter tilting drive is a well-proven technology and is in operation at many steel plants worldwide. The complete drive "rides" on the trunnion pin. Hence, the connection to the foundation is only the torque support. Particularly this torque support is a main feature of the Siemens VAI AOD equipment.

It is well known that the AOD converters are exposed to oscillation during the blowing process. This effect is much stronger in comparison to that of the LD converters. However, the oscillation is introduced by the bath itself and can be categorized as "self-exciting oscillation" driven by the gas bubbles and introduced streams in the liquid steel. The bath itself has a lowest eigenfrequency of typically 0.5 Hz. The corresponding eigenmode is basically a wave that shakes from one side to the other or a wave that rotates. The shaking of the liquid steel cannot be stopped during the excitation process (blowing). However, it is well known that oscillations become critical when the excitation frequency is identical or very close to one eigenfrequency of the system. When the damping in the system is small, the oscillation becomes instable and further damages can occur.

When applied to the AOD plant, this principle means that the eigenfrequencies of the system must not be anywhere near to 0.5 Hz. The eigenfrequencies of a mechanical system are basically determined by the stiffness and the mass. A typical relationship is shown for a single mass-spring oscillator below:



$$\omega = \sqrt{\frac{c}{m}} \qquad \text{(eq. 6)}$$

ω …... Eigenfrequency of the system [1/s]
c …… Stiffness of the system [N/m]
m ….. Mass of the system [kg]

Eq. 6 shows that the eigenfrequency increases for an increased stiffness and decreases for an increased mass.
In reality, a structure or fluid has an infinite number of eigenfrequencies and modes, but only a restricted number are exited and some of those are critical. One of the most critical eigenmodes is the oscillation of the converter around the tilting axes. During this motion the tilting drive, the gears, the brakes and the tilting support are exposed to additional forces and stresses. All other oscillations are supported more or less by the foundation itself and basically do not impact the mechanical equipment.
In order to reduce the impact forces to the tilting drive, Siemens VAI has developed the philosophy of keeping the stiffness of the torque support as small as possible. This stiffness is basically determined by the stiffness of the torsion bar (see Figure 5).
In a typical AOD converter based on this Siemens VAI design, the eigenfrequency of this motion is in the range of 1-2 Hz (depending on the masses of the system and the diameter of the torsion bar according to eq. 6).

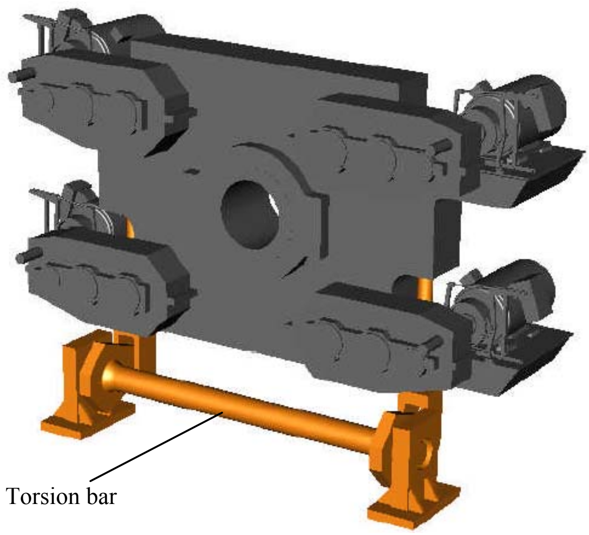


Figure 5: Siemens VAI converter tilting drive

This brings with it the following advantages:
- No resonance between eigenfrequency and exiting frequency of the liquid steel
- Impact forces in the system are kept to a minimum

However, in order to keep the impact forces within the teeth of the gears to a minimum value, the 2 (or 4) drives are preloaded to each other in the blowing position. This pre-loading is introduced electrically by fixing one motor with the brake and turning the other electric drives until a certain torque is reached. Then the brakes of those motors are released and the electric energy is shut off. Consequently, the pre-stress is frozen in the gear box and any knocking or other impact in the teeth is avoided.
Following this philosophy, the load during blowing (including dynamic effects) is less when compared to the maximum load during tapping, and consequently the tilting drive can be designed according to the maximum torque under normal operation condition (Figure 6).

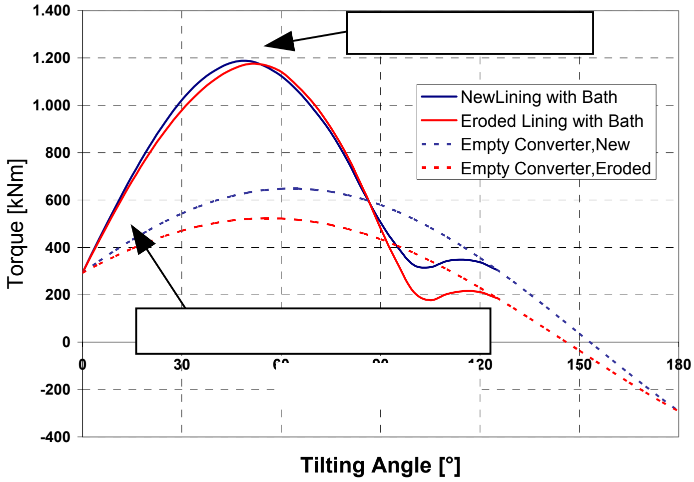


Figure 6: Tilting torques of a typical AOD

THE SUSPENSION SYSTEM

There are different designs available on the market. However, most of the suspension systems have a common, simple design based on wedges or swing bolts. Automatic suspension systems are also available on special request. These are operated by hydraulic cylinders. The philosophy of Siemens VAI is to apply suspension systems that are (basically) statically determined. This means that there are only three suspension elements that carry the main load of the converter during blowing.
Siemens VAI usually uses two different designs of suspension systems, depending on the vessel size.

- VAI-CON® Simple (for heat size < 50 t)
- VAI-CON® Quick (for heat size > 50 t)

VAI-CON® QUICK SUSPENSION SYSTEM

With the VAI-CON® Quick Suspension System, the converter rests on two saddles positioned in the area of the trunnion pins (for vertical and horizontal loads). The tilting torque is introduced via the third support on the rear side of the trunnion ring. In order to fix the vessel during rotation, two “swing bolts” are arranged at each support (see Figure 7). These bolts are usually fastened and unfastened by means of sledge hammers and heavy duty spanners. The nuts of these swing bolts rest on spherical washers on the vessel brackets. The pre-tensioning of these bolts is defined by turning the nuts during fastening by a specific angle only.

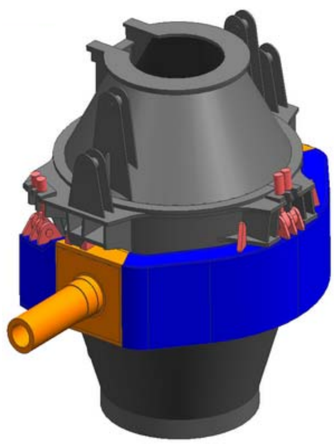


Figure 7: VAI-CON® Quick suspension system

During operation, the U-shaped trunnion ring opens due to thermal expansion. Consequently there is a difference in deformation between vessel shell and trunnion ring at the support positions. In order to compensate these differences and to avoid overstressing the swing bolts, they are arranged at optimized angles (α1) (see Figure 8). The angle of the front swing bolts is negative and the angle of the rear swing bolts is positive. However, during operation these angles are changed to smaller values $|\alpha_2| \leq |\alpha_1|$. The philosophy for these angles is to give the swing bolts the tendency to decrease tension in order to allow a quick and easy opening of the nuts for converter exchange. The relative motion is compensated by two spring cups and a spherical washer.
With these elements and arrangement the converter, the exchange time is in the range of 60 to 90 min (regularly).

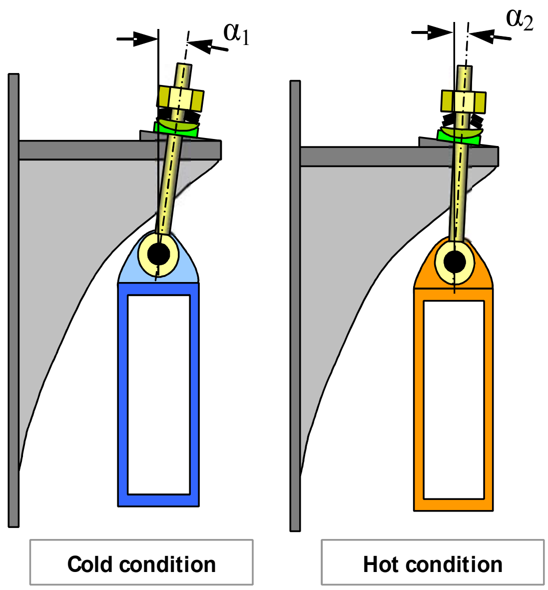


Figure 8: Changes in angle of front swing bolts during operation

The exchange time of the converter is dependant on several items:

- Access to the bolts and nuts depending on skull formation (cleaning necessary)
- Availability and readiness of all necessary equipment
- Teamwork of skilled operating and supporting personnel
- Optimized logistics
- Platform and other aids in order to simplify the work and protect the individuals (safety items).

The converter exchange time clearly affects the productivity of the steel plant (annual production). Assuming an average refractory life time of about 120 heats, the converter has to be changed approx. 35 to 50 times a year, which means approx. 50 to 80 h less production time per year due to converter exchanges.

FEATURES FOR DECREASING THE EXCHANGE TIME

As mentioned before, the exchange time depends on several pre-conditions. However, in order to decrease the total exchange time, a decrease of all individual steps is helpful in any case.
Based on the experience of Siemens VAI, an investigation was conducted in order to find potentials for decreasing the exchange time. The results were as follows:

- Automatic coupling of the tuyere connections (VAI-CON® Joint)
- Automatic clamping of suspension system (VAI-CON® AutoFix)
- Moveable converter equipment (platform car)

THE VAI-CON® JOINT SYSTEM

Siemens VAI has gained a lot of experience in automatic coupling systems for media supply. Examples are the VAI-CON® Quick Lance Coupling for blowing lances and sub-lances or the automatic water coupling in the segments of continuous casting machines. Siemens VAI consequently applied this principle to connect the media supply for process-gas as well as inert-gas blowing.
Figure 9 shows the principle for connecting a single line process-gas supply and 6 individual inert-gas lines. The connection block is placed on the trunnion ring in an optimum position. When the converter is put into the trunnion ring, all media supply lines are automatically connected and sealed within this block. Hence, there is no manual work necessary at all. Consequently, the safety is improved and the exchange time is reduced.
The total exchange time should be reduced by approx. 10 minutes (based on a regular converter size).

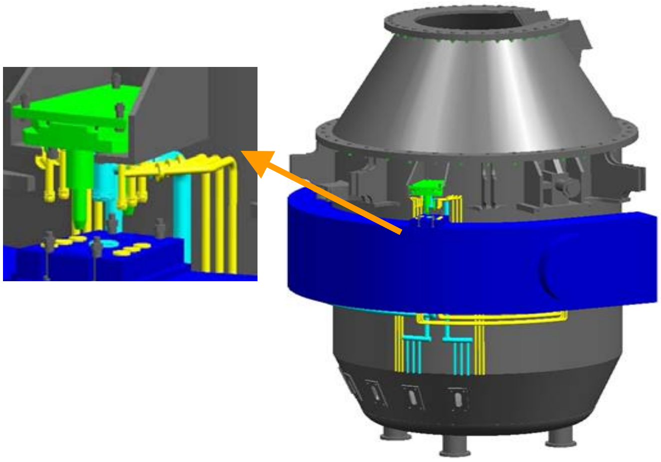


Figure 9: VAI-CON® Joint automatic media coupling system

THE VAI-CON® AUTOFIX SYSTEM

In order to also avoid any manual operation for the suspension system, Siemens VAI continuously improves the equipment. In the early seventies, Siemens VAI has already developed a fully automatic suspension system based on three suspension pins that are fixed to the trunnion ring by a hydraulic fastening system. This application is installed at the 180 t LD converter in Oxelösund (Sweden). Based on this experience, Siemens VAI has conducted studies for more cost-effective solutions in order to meet the actual requirements of the industry. The latest version is the VAI-CON® Auto Fix system. The idea is to use the VAI-CON® Quick suspension system as basis but to avoid the swing bolts by using a fully-automatic system to fix the vessel to the trunnion ring.

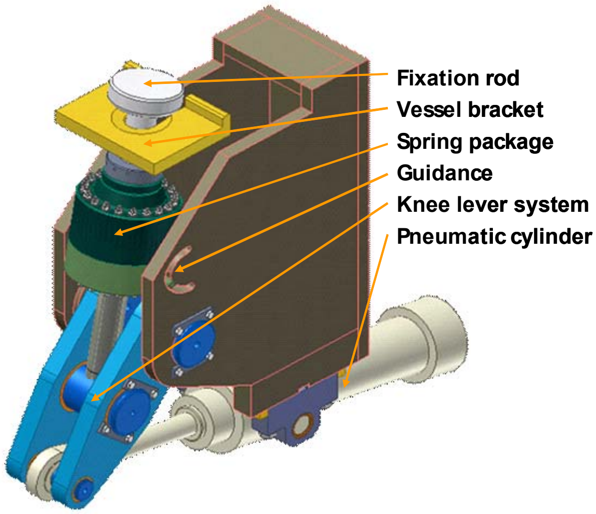


Figure 10: Fixation element of VAI-CON® Fix suspension system

The fixation is provided by a knee-lever system, which is activated by a pneumatic cylinder (see Figure 10). When the fixation rod comes in contact with the vessel bracket, the knee-lever system moves to a dead point, the spring package is activated and the vessel shell is fastened safely. Then the pressure of the pneumatic cylinder is released and the converter is ready for operation.

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