Mitigation of explosion risk in vacuum degassing plants

With the introduction of mechanical vacuum pumps for degassing, methods of efficient gas cooling and dust separation become necessary to avoid the risk of a combination of a critical off-gas composition along with an ignition point resulting in an explosion. This article reviews how to undertake a risk assessment and looks at equipment to mitigate the risk.

By Wilhelm Burgmann* & Uwe Zöellig**

IN all processes of vacuum steel degassing, the gases and vapours formed may be dangerous if they combine with oxygen at high temperatures or combine together. Also, inert gases, such as N2 and Ar, that are used in the process, also require careful handling because of the risk of suffocation.

Generally, CO and H\textsubscript{2} – as well as the vapours of volatile metals – are released. The metal vapours condense on colder areas of the plant and are partially oxidised to form a fine dust, which must be collected in special containers, cyclones and bag filters to prevent them reaching the vacuum pumps.

The flammable gases CO and H\textsubscript{2} can only ignite when there is sufficient oxygen present and the temperature is high enough, at which point there is a danger of an explosion (Table 1).

Different oxygen sources

Besides temperature, the oxygen concentration in the off-gas is important as oxygen may react with metal vapours and the temperature is high enough, at which point there is a danger of an explosion (Table 1).

Off-gas composition

The off-gases are composed of:
* plant air and plant humidity mainly from the refractory lining;
* leakages of air, cooling water and gases that are connected to the plant under pressure such as Ar, O\textsubscript{2}, N\textsubscript{2};
* gases H\textsubscript{2}, H\textsubscript{2}O, N\textsubscript{2} and CO that are liberated from the melt and the slag plus their oxidation products H\textsubscript{2}O and CO\textsubscript{2};
* equilibrium oxygen resulting from CO – post combustion;
* vapours of volatile metals (Mn, Zn, Pb, Cd) degassed from the melt, that also include the basis metals (Fe, Cu, Ni, Cr) depending upon the final pressure;
* Mg-vapours by reduction of MgO;
* Sulphur vapours caused by their very low vapour pressure – these cannot generate a notable desulphurisation, but after oxidation they can form aggressive

<table>
<thead>
<tr>
<th>CO</th>
<th>H\textsubscript{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower explosion limit LEL (in air) (%)</td>
<td>12</td>
</tr>
<tr>
<td>Upper explosion limit UEL (in air) (%)</td>
<td>75</td>
</tr>
<tr>
<td>Minimum oxygen concentration MOC (%)</td>
<td>5.1</td>
</tr>
<tr>
<td>Self-ignition temperature (°C)</td>
<td>605</td>
</tr>
<tr>
<td>Temperature class T1 (°C)</td>
<td>&gt;450°C</td>
</tr>
</tbody>
</table>

Table 1 Limits of flammability for CO and H\textsubscript{2}[1][2]

Oxygen is, therefore, a large uncertainty factor while determining any explosion hazard. As the minimum oxygen concentration is measured under specific conditions very different from the reality inside a steel degassing system or vacuum pump, it has been proposed to use only 40% - 60% of the MOC value when making a risk analysis[3].

The limits in Table 1 are indications for atmospheric conditions. Under vacuum conditions or at high concentrations of inert gases such as Ar, N\textsubscript{2} and CO\textsubscript{2}, these limits are shifted towards a narrower range (Fig 1). A similar influence of vacuum on the limit values has also been found for other fuels[4].

In Fig 2, the ternary system Oxygen-Fuel-Inert gas with the flammability range and the typical off-gas ranges of various vacuum processes are shown.

Suppression of flammability by dilution with inert gases would shift the ignition temperature to higher values[5,6], but would require very large amounts of inert gas and thus a substantially increased pump capacity with higher investment and operating cost.

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October 2014
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VACUUM DEGASSING

acids when combined with humidity;
• vapours of liquids that are used as
  sealing elements in the pumps (eg water
  and oil);
• gases that are deliberately added to
  the melt, such as Ar or N₂;
• gases that are deliberately introduced
to the pumps such as air or N₂ with
the aim of gear box isolation or for cooling,
cleaning or rinsing of rotors or casings.

Fig 3. and Fig 4. demonstrate typical off-
gas compositions according to computer
models for the RHO and VOD degassing
processes. The peak concentrations of CO
and H₂ are recorded in the literature[7].

Forced decarburisation in VD-OB, RHO
and VOD processes generally leads to
higher CO concentrations. The oxygen top
blowing lances that are usually installed
generate an imperfect coherent gas jet
with a limited penetration depth. The
resulting post-combustion of CO to CO₂
increases the concentration of inert gas
(Ar, N₂ and CO₂) in the off-gas. Also the
vessel pressure is low in all cases.

These two conditions – a high
proportion of inert gas and low pressure
in the hot reaction vessel – are sufficient to
avoid explosions of CO or H₂ under regular
operation conditions.

Dust formation and handling

The formation of dust from oxidised
metal vapour condensate is typical for all
vacuum processes. The amount of dust
its degree of oxidation and its grain size
vary significantly between the different
processes. Operational experience shows
that up to 0.25kg/t of dust are formed in
the VD-process, and in the decarburising
processes about 1kg of dust per kg carbon
removed, ie 0.6kg/t in RHO and 4-8kg/t
during VOD treatment. The grain size is
50% in the range of 0.2 to 1.5µm for the
VD-process and up to 5µm in the oxidising
processes.

For a detailed risk analysis the vacuum
plant must be divided into three sectors:
• The metallurgical reaction vessel in
which the vapours and dust are formed;
• The connection between vessel and
vacuum pump, in which the vapours
condense and where dust is deposited or
separated; and
• The vacuum pump set.

Since all metal vapours have a greater
affinity to oxygen than for H₂ and CO,
any oxygen that might be present under
vacuum reacts preferentially with these
metals and so reduces the concentration of
oxygen in the off-gas composition. Because
of the limited oxygen concentration it is
possible that the condensed dust particles
are not fully oxidised and, therefore, retain
a tendency to burn.

For this reason, nitrogen is typically
used as an inert gas for partial flooding,
cleaning and conveying dust in all plant
areas where dust may be deposited.

The formation of dust and the conveying
of dust do not occur simultaneously inside
the vacuum plant, which is operated in a
batch-wise way. Dust is generated in the
hot impact area of an oxygen lance during
forced decarburisation at about 100hPa
and is partly separated from the off-gas in
large volume areas or transported by the
off-gas towards cyclones and dust filters
or directly towards the vacuum system
(as far as these are prepared for such
dust absorption such as steam ejectors or
water ring pumps).

During degassing at 10 to 1hPa
evaporation becomes more intensive.
However, the dust transport occurs to
a reduced extent owing to a lack of
gas density. The vapours condense and
accumulate in the areas prepared for this
purpose but also in the suction duct.

At the end of a vacuum treatment
the pump set and the area designed
for separating the dust are isolated and
partially vented with nitrogen, the other
plant areas are vented with air.

When a new vacuum treatment cycle
is started the complete plant comes in
contact with air again including those
areas with dust deposits. During the initial quick pump down, high mass flows of gas occur for a short time with high flow rates. The dust that is deposited in the suction pipe from the preceding vacuum treatment is then whirled up and conveyed as a dust cloud. At this moment the gas atmosphere does not contain any flammable gases and the gas temperature measured at the pump inlet is between -5°C and +45°C.

Dust separating devices are essential for any mechanical pump set. In many cases bag filters with over-pressure flaps are followed by instruments that semi-quantitatively measure dust concentration; alternatively, so-called filter guards are installed at the cleaned gas side.

Separation of dust is very efficient at >99%. The residual emission on the filters’ clean gas side is <10mg/Sm³ as an average value of a cycle, even with much higher short time peaks. Cleaning the filters with nitrogen is automatic after each vacuum treatment cycle. Dust deposits are avoided by using a steep angle in the dust catching funnel and by systematic discharging of the separated dust. Dust, therefore, does not create an additional risk for the pump set so there is no need for any supplementary risk analysis to prevent dust explosions.

**Risk analysis**

Modern vacuum plants with a low danger potential are characterised by very low leak rates, good control of the refining process and reliable dust handling. However, the plant user must be prepared for breakdowns and an erroneous process control and must be prepared for such rare cases by following the guideline ATEX 137[9,10], again by sub-dividing the plant into vessel, gas preparation line and pump set.

The off-gas composition, the low absolute pressure and the high temperatures in the metallurgical reaction vessel of vacuum plants – such as from induction furnaces, hot ladles, converters or RH-circulation vessels – are not alone indicative of the flammability of gases and, therefore, fires or explosions in the complete plant.

If any off-gas analysis or off-gas calculation reveals a harmless situation inside the vacuum reaction vessel or gas preparation line, it must be considered that when such a gas mixture is again brought to atmospheric pressure in the vacuum pump set, this might lead to undesired reactions inside the pump set or in the exhaust.

Leakages or a planned addition of air into the line between the metallurgical reaction vessel and the vacuum pump set would be particularly dangerous[3].

Any necessary gases for ballast, isolation, purging or cooling of the pumps should, therefore, be with inert gases. This especially concerns the pre-inlet cooled Roots pumps and endless screws with high continuous air bleeding. In this respect, see the ternary gas diagram Fig 2.

A gas composition that is harmless in the vacuum vessel could become critical at the pump set. Hot particles in the gas or hot elements of the plant can be ignition sources. In unfiltered off-gas lines, as is usual for steam ejectors and water ring pumps, hot particles conveyed along with the gas can be ignition sources.

In plants with mechanical vacuum pumps, even with carefully filtered and cooled off-gas lines, several ignition sources are possible:

- Surfaces that are overheated by compression and internal friction and hot gases;
- Mechanically generated particles, which are generated by frictional contact between moving pump elements or by the introduction of foreign bodies[12];
- Electrical sparks inside the pump caused by electrostatic discharge;
- Chemical reactions inside the pump set.

As a first step, the plant user has to define explosion zones by the application of the working area directive ATEX 137[9,10]. Following this, equipment has to be selected which fulfils the requirements of the defined zone.

The equipment directive ATEX 95[11] distinguishes the following equipment categories presented in Table 2.

The VOD process may be considered as the worst case degassing process[13]. According to the applicable definitions, zone 1 and category 2G (interior) could be determined for this process. Also for other oxidising processes, such as VD-OB and RHO, as well as the reducing processes

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**Table 2**

<table>
<thead>
<tr>
<th>Equipment Category</th>
<th>Equipment Zone</th>
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<tbody>
<tr>
<td>1</td>
<td>2G</td>
</tr>
<tr>
<td>2</td>
<td>2G</td>
</tr>
<tr>
<td>2G</td>
<td>2G</td>
</tr>
<tr>
<td>3</td>
<td>2G</td>
</tr>
</tbody>
</table>

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**Fig 4.** Typical off-gas composition of a 125t VOD melt for high-chromium bearing steel grades with initial (C+Si) >0.5%. (calculated)

**Fig 5.** CO, CO₂ and O₂ proportions measured during a 125t – VOD treatment (starting C+Si concentration <0.22%)[8].

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October 2014
VCD and VD, this zone and category should be applicable.

For the pump system no exterior explosion zone is a concern.

In additions to the explosion zones, the explosive gas mixture has to be assigned to the appropriate temperature class and gas category. The temperature class depends upon the surface temperature at which the gas mixture could ignite. The explosion class for CO is IIB and for H2 IIC as in Table I.

**Solutions**

There are pumps and components on the market that fulfil the ATEX Cat 2 (i) G IIC T1 specification and these can be combined by recognised and certified vacuum pump manufacturers to build complete vacuum systems.

The ATEX solution for complete steel degassing plants must consider the following directives and standards:-

- Directive 94/9/EC for ATEX equipment[10];
- European Standards for explosive atmospheres[11,12];
- Highly overengineered vacuum pump systems.

Regarding the vacuum pump set, the ignition sources already defined have to be considered in terms of what may be achieved during design and manufacture of ATEX-certified pumps. In particular the pumps must be protected against overload by too high a pressure difference to avoid generating excessive temperatures. This is valid for all possible operating points starting with high suction pressures, passing to medium operating pressures which need to be held over a longer time as, for example, during delayed pump-down in the VD process or during the oxygen blow phase of the VOD process, and down to the lowest end pressures with its high compression ratios.

The most secure method to avoid such overload is achieved by a sophisticated drive control with an adjustable torque limiter for the motor. This makes most of the costly ATEX-compatible sensors for pressure and temperature obsolete and, in addition, results in a shorter pump down-time.

Other safety measures that must be taken are:

- Installation of sieves at the pump inlet or suitable upstream filters to withhold larger particles that might cause ignition;
- Gas cooling in order not to exceed the admitted pump inlet temperature (40-80°C depending upon the pump type);
- Use of gearbox oil of defined electrical conductivity to avoid static loading and with proven oxygen compatibility in case of an uncontrolled oxygen refining process.

After execution of the necessary tests, the relevant ATEX documentation must be submitted and stored at a notified body so that third parties can access it.

The usual mechanical vacuum pumps for steel degassing are endless screws and Roots pumps. **Fig 6** shows the essential means to avoid ignition sources in these pumps:-

- Hermetic tight design with leak rates <0.1hPa-liter/sec;
- No dynamic seals against atmosphere;
- Integrated water cooling to make the pump independent of the ambient temperature;
- Highly efficient ATEX-compatible encapsulated motor, avoiding magnetic or other couplings;
- Long-life oversized bearings which enable long maintenance intervals of up to four years;
- Antistatic greasing to avoid electric loading inside the pump;
- Frequency converters with overload protection, thus fewer sensors;
- Automatic alarm of insufficient cooling;
- Automatic alarm of inadmissible overpressure at the exhaust side.

The suggested design solution for an ATEX-certified standard pump module according to EN 13463-1[116] Ex II2/-Gc IIC T2 Gb is shown in **Fig 7**.

Several modules designed according to this layout are under construction for the RHO process.

**Conclusions**

Explosion protection in vacuum plants, especially those generating a large quantity of CO by the use of oxygen for decarburisation, has so far been assured by the use of overpressure flaps at/on the metallurgical reaction vessels, alarm devices for water leakage, sensors for pressure and temperature as well as emergency venting with nitrogen.

Following the introduction of mechanical vacuum pumps, efficient installations for gas cooling and dust separation have become necessary.

Continuous off-gas analysis, which is standard for VOD plants for process control using whatever vacuum pump system is employed, is not necessarily optimised to avoid explosions. Knowledge
that there is a flammable gas mixture is insufficient to prevent ignition.

The user should understand that the use of primary pumps cooled by an air-inlet is not recommended since they operate independently of an ignition source and the oxygen content is always high.

Mechanical vacuum pumps meeting higher standards are available to fulfil safety requirements including pressure shock resistance of up to 10 bars according to EN 1012-2. However, their use does not automatically mean that they are not an ignition source for gas mixtures. In cases where there are uncertainties regarding the flammability of gas mixtures in the pump sets, this problem can be solved for all vacuum processes effectively with an ATEX - certificate zone 1, category 2 (interior) pump for gases. The user, therefore, can reach the highest safety standard for people and equipment at a relatively low investment.

To prevent a potential excess gas-temperature, additional gas cooling and temperature monitoring should be installed between each pump stage. All pumps are regulated and monitored by specially programmed frequency converters.

The gas mixture and ignition possibilities described in this article are typical for the VOD-process. The same considerations are valid for all vacuum processes with forced decarburisation such as VD-OB and RHO.

The off-gas composition and the moment of appearance of a flammable mixture are very different in each of these processes. The ATEX-equipment described is also a solution for these situations.

The user should make a risk analysis regarding gas composition and ignition sources for the whole vacuum plant including reaction vessel, suction pipe, shut-off gear, cyclone, cooler and filter. ■

References