Gas adsorption in air vessels
Double hose-diaphragm pump with in-built compressor

Heinz M. Nägel

Diaphragm pumps rank among the most popular versions of hermetically sealed oscillating displacement pumps and fulfil various metering, feeding or transport tasks in process industries. The limits of operational capability are not only determined by the medium to be conveyed and its characteristics, but also by the pressure pulsation as a result of flow rate fluctuations. Especially when considering steep system characteristics, air vessels are essential to prevent damage to the equipment. Air vessels are therefore used for dampening of pressure fluctuations of piston, diaphragm or piston diaphragm pumps, which do not generate a continuous flow rate due to their design.

Pulsations of oscillating displacement pumps

Due to the constantly changing piston displacement of oscillating displacement pumps, with each stroke the entire contents of the suction and discharge lines must be accelerated and subsequently decelerated. Particularly with high pressures and long pipelines, pressure fluctuations are unavoidable because the medium is conveyed solely during the forward piston stroke, i.e. for the duration of one-half of the total stroke.

The intensity of pulsations is directly related to the flow characteristic of the chosen pump design. By comparing the various flow curves, it is evident that the degree of irregularity is significantly smaller with an odd number of cylinders than with an even number. Therefore pumps with an odd number of cylinders are preferred. Normally Triplex units (see fig. 1) present a useful compromise between mechanical effort and pulsation behaviour, consequently damping can be achieved with acceptable effort. Therefore they are known as the most efficient type of process pumps. Should the flow rate of Triplex pumps not be sufficient, or the application is subject to changing operating pressures where reliability and/or pulsation reduction is highly desirable, Quintuplex units are usually specified (see fig. 2).

Taking the example of hydraulically activated double hose-diaphragm pumps, the following text shows measures of effective pulsation dampening. Double hose-diaphragm pumps (see fig. 1 and 2) represent the newest generation of hydraulically activated diaphragm pump type. Due to its unique technical and economical characteristics, this pump design is especially used for critical applications, chemically aggressive and mechanically abrasive fluids and highly viscous media with various consistencies. Depending on the medium, the dry matter content can be up to 80%. For heterogeneous mixtures, i.e. for media that tend towards fast sedimentation, special designs with Down-flow technology (see fig. 3) are available. Down-flow technology, as it states, allows the pumped media to travel through the pump from top to bottom. In doing so, the cylindrical shape of the diaphragm favours flow characteristics and reliably prevents sedimentation inside the pump. Furthermore, the processes of SIP and CIP cleaning are effectively supported.
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Gas adsorption in air vessels

Normally pulsation dampeners are used for reducing pressure and flow rate fluctuations, as well as smoothing of resultant pressure surges. Now only the conveyed medium between pulsation dampener and piston must be accelerated and decelerated, whilst the flow velocity inside the pipelines remains almost constant. To keep the medium mass accelerated by the pump stroke as low as is practicable, the pulsation dampeners must be installed as close as possible to the pumps.

The best-known design of traditional pulsation dampeners for oscillating displacement pumps are gas-filled dampeners, so-called air vessels. In principle, the air vessel consists of a container partially filled with air. With the standard design, direct contact between conveyed medium and air cushion is

Fig. 2: Quintuplex double hose-diaphragm process pump. Ideal design for applications with large flow rates and variable pressure, e.g. hydrotransport.

Fig. 3: Down-flow technology (medium transportation from top to bottom) for heterogeneous mixtures and media with coarse solids.

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unavoidable. The air vessel’s effect depends on the air volume that serves as a cushion for the arising pressure peaks. It is compressed with each pressure stroke and decompressed during the suction stroke, so that only small flow rate and pressure fluctuations remain (see fig. 4). The pressure fluctuation inside the air vessel is primarily dependent on the discharge head, the pulsation volume of the connected pump and only to a small extent on the flow resistance.

With each pump stroke the fluctuation volume will be removed from the dampener and fresh fluid is preferably fed to the dampener. The following applies:

\[
\frac{\Delta p'}{P_a} = \kappa \cdot \frac{\Delta V}{V_{Gas}}
\]

According to the Henry law, at increased pressure gas is deposited into the fluid and is therefore lost from the air vessel. As a result, the air vessel will progressively lose its ability for damping of flow rate fluctuations.

The gas compression behaviour can be relatively well described by means of the ideal gas law. The full pressure fluctuation range \( \Delta p' \) based on the average pressure \( P_a \) complies with the quotient of the product of isentropic exponent \( \kappa \) and fluctuation volume \( \Delta V \) and gas volume.

In many cases air vessels are the only solution. Their low-pressure drop at the suction side inlet is ideally suited for the use in suction lines. For highly heterogeneous media (e.g. slurry) or extremely corrosive chemicals, an air vessel at the suction side is often the only alternative. The problem with air vessels, however, is that the medium is generally gas soluble and therefore reduces the gas filling of the air vessel with every stroke. This is not tolerable and therefore requires measures for optimal compensation of the gas loss. Furthermore, knowledge of the required amount of gas per stroke is essential.

The gas composition behaviour can be relatively well described by means of the ideal gas law. The full pressure fluctuation range \( \Delta p' \) based on the average pressure \( P_a \) complies with the quotient of the product of isentropic exponent \( \kappa \) and fluctuation volume \( \Delta V \) and gas volume.

The air vessel is partially filled with gas. The remaining space is comprised of the conveyed medium. A thin barrier exists between medium and air, over which an exchange of substance takes place. In the process, balance on both sides of the barrier occurs. This balance can be described with the dimensionless Henry constant \( K' \), which shows the ratio of gas concentrations in the gas \( C_G \) and water phase \( C_W \) after theoretically unlimited time. Thus, it can be assumed that this barrier constantly renews itself by means of the dynamic inside the dampener, resulting in extensively uniform charging. The coefficient applies as follows:

\[
K' = \frac{C_G}{C_W}
\]

\[
\Delta p' = \kappa \cdot \Delta V
\]

\[
P_a = \frac{\Delta V}{V_{Gas}}
\]

Fig. 4: Pressure curve at 15 bar (Simplex pump, flow rate 2.5 m\(^3\)/h, air vessel volume 10 litres at 1 bar “pre-compression”. A parabolic load without static height is assumed as the characteristic curve, thus showing pure friction with \( H \) proportional to \( Q^2 \)

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Due to the design of the air vessel and its flow during charging and discharging, fluid mixing can be considered as sufficient. Therefore, it can be assumed by approximation that the liquid inside the dampener is mostly uniformly charged with gas. Thus the dampener’s fluid content can be used for gas adsorption volume.

How much air is dissolved and therefore has to be re-filled is, however, also dependent on the operating data (stroke frequency and pressure). The average pressure is introduced approximately. Since the Henry law indicates a linear connection between gas dissolution and pressure, then this is valid. The dissolution time refers to a pump cycle, or the average duration of stay of the fluid inside the dampener.

Solution equilibrium

The air vessel is partially filled with gas. The remaining space is comprised of the conveyed medium. A thin barrier exists between medium and air, over which an exchange of substance takes place. In the process, balance on both sides of the barrier occurs. This balance can be described with the dimensionless Henry constant \( K' \), which shows the ratio of gas concentrations in the gas \( C_G \) and water phase \( C_W \) after theoretically unlimited time. Thus, it can be assumed that this barrier constantly renews itself by means of the dynamic inside the dampener, resulting in extensively uniform charging. The coefficient applies as follows:
Concentration ($C_G$) in the gas phase can be described as the quotient of partial pressure $p$ and the product of gas constant $R$ ($=0.081 \text{ bar-L/mol-K}$) and the temperature. This is denoted by the unit mol/L.

$$C_G = \frac{p}{R \cdot T}$$

From both equations the Henry law follows in its most common notation

$$p = K_H \cdot C_W$$

with the Henry coefficient

$$K_H = R \cdot T \cdot K'_H$$

Often an inverse notation is used, however, for the equilibrium concentration of gases in water

$$C_W = \lambda \cdot p$$

With gas solubility

$$\lambda = \frac{1}{K_H}$$

High values of $\lambda$ characterize good gas solubility in liquid. This also shows that solubility of gases is directly proportional to the pressure. Hence, the solubility increases linearly with increasing pressure and decreases when pressure drops. The assumption in terms of solution decisiveness for the average pressure is therefore valid.

**Temperature dependence**

The solubility of gases in water decreases with increasing temperature. They are mostly determined empirically. The following values apply according to [1]:

According to this, the solubility decreases by approximately 10% per each $5^\circ \text{C}$ temperature increase.

<table>
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<th>$T$ (°C)</th>
<th>$N_2$</th>
<th>$O_2$</th>
<th>$Ar$</th>
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<tr>
<td>25</td>
<td>0.0177</td>
<td>0.0398</td>
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</tr>
</tbody>
</table>

Table 1: solubility $\lambda \,[\text{g/L-bar}]$ of gases in water

**Saturation**

The sum of all partial pressures of gases dissolved in water must be smaller than the total water pressure, otherwise bubbling will occur. Therefore:

$$p = \sum p_i = \sum \frac{C_{Wi}}{\lambda_i}$$

**Gas exchange**

Gas exchange takes place by means of the barrier. An exchange of substances through molecular diffusion takes place within the barrier. With a good mixture inside the phases, concentration gradient will only occur in the thin barrier. Barrier thickness depends on surface movement. For small velocities, such as inside the air vessel, the barrier thickness $h_B$ can be estimated with 10 $\mu$m. However, the flow-induced mixing is certainly so good, that in extreme cases the charging of the liquid dampener volume $V$ ($p, t, K$) can be assumed as uniform. Thereby the approximate stroke volume going into the dampener is filled with gas on each stroke and then again discharged from the dampener. For a Simplex pump, this value is assumed to be 55% of one stroke volume. For a Triplex pump it is approximately 10% and for a Quintuplex pump approximately 7%. Therewith the volume exchange of a Simplex pump is the highest and with multiple acting pumps measured from the dampener size, is relatively small. For this reason, the average fluid duration inside the dampener of these pumps typically covers several stroke cycles, allowing the assumption of a uniform charging up to a specific barrier. However, according to [1] the saturation time for oxygen inside water is more than 100 minutes for a vessel that is stirred with 200 l/min. The situation inside the dampener is therefore far from gas saturated. With approximately three rotations per minute the stirring process can be considered as very close to the fluid behaviour inside the dampener, thus giving certainty to the following calculation.

If the conveyed fluid is saturated when exiting the dampener, the gas concentration gradient is calculated as follows:

$$C_W = \lambda \cdot \Delta p,$$

whereas, $\Delta p$ represents the average pressure increase inside the pump.

Consequently, there are various velocities for various gases, since diffusion coefficient and solubility depend on the material.

For the main components of air, nitrogen and oxygen, the diffusion coefficient DW is almost the same and amounts to approx. 2.0–2.5x10$^{-3}$m²/s. Hence the data from [1] can be used!

An average pressure of 1.6 bar results in a substance flow for air of approximately

$$C_W = \lambda \Delta p = 0.024 \text{Kg} / \text{m}^3 / \text{bar} \cdot 16 \text{bar}$$

$$= 0.384 \text{Kg} / \text{m}^3 = 0.384 \text{gr} / \text{Liter}$$

This would mean that 384 standard litres of air are lost with each litre of liquid that is discharged from the dampener. However, by evaluating the diagrams in [1] it shows that the dissolved gas volume is <1% of the saturated condition after one second. Thus, a maximum of 3.84 standard litres are lost with each litre of liquid. Therefore, a dampener for a Simplex pump with a stroke volume of 1.8 litres would lose exactly this air content with each stroke cycle. For multiple acting pumps this would be proportional.

Undoubtedly this is a not an insignificant occurrence, which would lead to complete discharge of the damper after a few hours.

**Re-fill flow rate**

To counteract the disappearance of the gas cushion, air must be conveyed
into the vessel. Assuming a clear diameter of 100 mm inside the air vessel (4L), 120 cm³/h must be re-filled to achieve the visualized uniformity shown in fig. 7 and 8. The traditional inflation is complex and complicated, but mainly because the fluid level must be constantly measured and the gas volume replaced by a separate compressor, if necessary. In addition, the individual gas filling coordination in terms of operating principle, operating time, pressure, conveyed and medium etc. is inevitable. During the supplying of air (by means of a stationary compressed air system) it must be ensured that no conveyed media reaches that system, e.g. through a leaking filling valve!

The characterized double hose-diaphragm pump is designed as a modular concept, ensuring that the piston rod can optionally be used for an in-built compressor in order to guarantee optimal and reliable ventilation of air vessels, regardless of whether single, double or quadruple acting pump configuration is concerned (see fig. 6).

The in-built piston compressor reliably ensures that a small amount of filtered air (or gas) is drawn into the compressor cylinder with each return stroke, by means of a valve. During the piston rod’s forward motion, this amount of air is fed into the air vessel through the incorporation of a non-return valve. This process repeats itself continually with each pump stroke and only occurs if the pump is operational. In this way, the existing air volume is, optimally, added and residual pulsation is reduced to a minimum.

An in-built compressor with a displacement volume of approx. 50 cm³ (D 30 mm x L 70 mm) attains a volume of almost 1 cm³ with each stroke (see fig. 6) and is therefore able to compensate the adsorption and to ensure a very low-pulsation (see fig. 7) and uniform conveyance (see fig. 8). For applications that require frequent and fast inflation of air vessels, it is possible to supply the in-built piston compressor with pre-compressed air at the suction side.

Pressure of the in-built compressor is always significantly higher than the maximum pump pressure. This guarantees that no medium reaches the in-built compressor under normal operating conditions. By adopting this inbuilt compression device over the aforementioned stationary plant
Since the Pump is the Heart

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