Oscillating Displacement Pumps
Performance and Characteristics of Positive Displacement Pumps

5th OMB conference Nanjing
Presentation - Shicheng Hall - on November 7, 2016

Heinz M. Nägel
Oscillating Displacement Pumps
Performance and Characteristics

Contents:
• Pump Characteristic
• Pump Heads
• Ideal Principle
• Application Ranges
• Head – Conveying Properties
• Influence of the Medium
• Comparison between Piston and Diaphragm pump
• Self-acting Valves – Typical design
• Pulsation Dampeners
• NPSH
Pump Characteristic Curves
Characteristic conveying curves

Pressure stiff means: \( p, H \)
Low loss due leakage and compressibility

Pressure stiff is a precondition for dosing processes

\[
p = f(V)
\]

Plant curve

\[
\Delta p \quad \Delta V
\]
Oscillating Displacement Pumps Pump Heads

- Up to 20,000 bar
- < 800 bar
- < 350 bar
- < 400 bar

- < 500 °C
- < 150 °C
- < 200 °C
- < 130 °C

- < 16 bar
- < 5 bar
- < 5 bar
- < 200 bar

- < 80 °C
- < 80 °C
- < 100 °C
- < 200 °C

Heinz M. Nägel 2016
Oscillating Displacement Pumps
(Piston Pump including suction and discharge air vessel)
Oscillating Displacement Pumps
Application Ranges

\[ p = \text{vacuum up to 20 000 bar} \]

Flow: 5 ml/h up to 300 m³/h

\[ V_{th} = V_h \cdot n \]

Viscosity up to 1500 Pas

\[ \dot{V} = V_{th} \cdot \eta_v \]

T = -270 up to 500°C

Hermetic design: diaphragm pump

Fluids: toxic, abrasive, aggressive, corrosive, suspensions
Oscillating Displacement Pumps
Pump Volumetric Efficiency/Dead space

The dead space reduces the real stroke volume. The loss gets visible via the duration of the expansion process.

Dead space ration:
\[ \varepsilon = \frac{V_{DS}}{V} \]

Fluid compressibility:
\[ \chi = \frac{\Delta V}{V \Delta p} \cdot \frac{1}{E} = \frac{1}{k} \]

The bigger the compressibility, the smaller the dead space should be.
Oscillating Displacement Pumps

Pump Volumetric Efficiency

Elasticity of the parts / liquid

\[ \eta_V \approx 1 - \left( \varepsilon_T k + \lambda_{AR} \right) \Delta p \]

Steel:
- \( E = 210\,000 \, \text{N/mm}^2 \)

Water:
- \( E = \sigma/\varepsilon \)

z.B. \( p = 100 \, \text{bar} = 10 \, \text{N/mm}^2 \)
- \( \varepsilon = 0,5\% / 100 \, \text{bar} \)

\( E = 2000 \, \text{N/mm}^2 \)

The elasticity of the parts \( \lambda_{AR} \) often can be ignored

\[ \lambda_{AR} = \frac{\Delta V_E}{V_k} \cdot \frac{1}{\frac{1}{\Delta p} = \frac{1}{E}} \]
Kinematics effect on suction and discharge piping system
Oscillating Displacement Pumps
Stroke Kinematics
Influence of the shaft-radius-ratio

\[ \lambda = \frac{r}{L} \]
Oscillating Displacement Pumps
Conveying Kinematics
Phase Cut – Pressure shock - Joukowsky Shock

\[ \eta_v^3 < \eta_v^2 < \eta_v^1 < \eta_v,\text{th.} \]

What happens with the valves?

\[ \Delta p_J = \rho \cdot c \cdot \Delta v \]

Discharge

Suction stroke

Pistonspeed \( V_k \)

Krankshaft angle

\[ \Delta v \]
Oscillating Displacement Pumps
Conveying Properties – Ideal Principle

Due a long and precise stroke

Consequences from the possibilities for failures

- Valve leakage
- Compression
- Expansion
- Suction

→ Avoid all!

Valve leakage
Compression
Expansion
Suction
Oscillating Displacement Pumps
Flow characteristic (Simplex pump)

Pump flow rate

Operating pressure [bar]
Oscillating Displacement Pumps
Flow characteristic (Duplex pump)
Oscillating Displacement Pumps

Flow characteristic Triplex pump

Pump flow rate

Operating pressure [bar]
Oscillating Displacement Pumps
Flow characteristic Quadruplex pump

Pump flow rate

Operating pressure [bar]

Heinz M. Nägel 2016
Oscillating Displacement Pumps Flow characteristic (Quintuplex pump)

Pump flow rate

Operating pressure [bar]

Heinz M. Nägel 2016
Oscillating Displacement Pumps

Pulsation dampening
Oscillating Displacement Pumps
Head Properties

Ideal Acting Principle

Pulsation!

Heinz M. Nägeli 2016
Pulsation Dampeners

- Air vessel
- Air vessel
- Bladder
- Traditional bladder
- Hose-diaphragm pulsation dampener
- Pulsorber
- Reciprocating pump system
Pulsation Dampener
- Adjustable Air Vessel System -

Prefilling before pump is started:
80% of working pressure

During operation: Pressure in air vessel is equal to working pressure

Air cushion

Medium

Inlet

Outlet

Pressure

Pressure
Pulsation dampeners are used for reducing pressure and flow rate fluctuations, as well as smoothing of resultant pressure surges.

Only the conveyed medium between pulsation dampener and piston must be accelerated and decelerated, whilst the flow velocity inside the pipelines remains almost constant. The air vessel’s effect depends on the air volume that serves as a cushion for the arising pressure peaks.

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.
Residual Pulsation

\[ \Delta p = \frac{p}{2} \cdot \kappa \cdot \frac{\delta \cdot V_K}{V_G} \]

- \(p\) \text{ bar} \quad \text{Operating pressure}
- \(\Delta p\) \text{ bar} \quad \text{Pressure fluctuation}
- \(V_K\) \text{ Liter} \quad \text{Displaced volume}
- \(V_G\) \text{ Liter} \quad \text{Active dampening volume}
- \(\delta\) \quad \text{Degree of kinematic irregularity}
- \(\kappa\) \quad \text{Isentropic exponent}
Oscillating Displacement Pumps

valves – Characteristics and applications
Oscillating Displacement Pumps
(Self-acting Valves – Typical Check valves design)

Valve types
• Ball valve
• Plate valve
• Cone valve

Always pressure balanced
Oscillating Displacement Pumps
Valves Second best design – classical piston pump

But! With optimal valves

• Matching the fluid properties
• Optimum geometry

Wear and closing delay should be minimal
Oscillating Displacement Pumps (Self-acting Valves)

Goal: Optimal tight valves with long duration

Problem: Opening and closing process

Correctives
- Manufacturing quality/precision
- Spherical balls
- Sharp seal geometries
- and ....safety...

Double ball valves
- Triple valve configuration
- More safety
- Special material balls

Closing delay!
Guiding quality
Sphericity of the ball
Adhesive effects
Double Valves

- Double valves are used for critical processes which do not allow interrupted flow.

- Double valves provide double safety against smallest leakages.

- Double valves reduce valve wear and increase maintenance intervals.
The valve opens after the air that is enclosed in the product, has been compressed to a pressure that exceeds the working pressure.

The resulting loss of pressure is compensated during the opening cycle.

This results in an overspeed that depends on the coefficient of the loss of pressure of the valve.

\[ v_{ü, EV} = \frac{\Delta p}{\sqrt{\frac{\rho}{\zeta V} \frac{\rho}{2}}} \]
Wear of ball valves
- Flow loss in double valves -

With double valve configuration the valve that is the closest to the pump opens first. Due to the low dead space within the valve, little flow is sufficient to increase the pressure to an extent that the second valve opens.

As a result of double pressure loss the overspeed is reduced accordingly.

Double valve configuration, as illustrated, allows for considerably extended life cycles.

\[
\nu_{\text{ü, DV}} = \sqrt{\frac{\Delta p}{2\zeta V \frac{\rho}{2}}} \]

\( p_0 + \Delta p/2 \)

\( p_0 + \Delta p \)
Ball Valve vs. Cone Valve

Ball Valve

- Valve ball
- Ball guide
- Valve seat (reversible)

Cone Valve

- Guide bush
- Cone top guide
- Compression spring
- Rubber ring
- Cone valve disc
- Valve seat
- Cone guide
Oscillating Displacement Pumps
Volumetric Efficiency Elasticity factor, quality factor

\[ \eta_E = \eta_{E,OVP} = 1 - \left( A \frac{y_{100}}{y} - B \right) \cdot p \rightarrow \text{All elasticities: fluid, oil, parts!} \]

\[ \eta_G = 1 - \left( C \frac{\Delta p}{\eta} \cdot \frac{n_{100} + V_R}{n \cdot V_h} \right) \rightarrow \text{All losses: Leakages!} \]

\[ \eta_G \text{ often very little!} \]

\[ \text{But wear changes !!!} \]

\[ \eta_V \approx 1 - \left( \frac{\varepsilon_T \kappa + \lambda_A}{\Delta p} \right) \]
Oscillating Displacement Pumps
Wear of valves

Valve seat

Worn out Valve Seat Removed from a high-pressure slurry pump
Energy Balance in Case of Leaking Check Valves
- Energy Loss in Case of Leaking Check Valves -

Leakage in discharge and/or suction valve

Power loss due to leakage (wear) in the discharge valve

\[ P_{VD} \leq P_{VS} \]

Effective Flow Rate

Suction stroke
1. In the case of high viscosities, particularly when the fluid is carrying particles, the following applies: The deformation/deflection of the natural flow lines should be kept as little as possible. Deflections, such as result from angle valves, affect the suction and cause the shearing effect.

2. The more gentle the product passes through the valves, the lower the wear rate.

3. Influence of pressure
   Special influencing value – Differential pressure in the sealing area. Examples: Abrasive particles in suspension can create a valve gap / leak. The prevailing pressure at the gap generates high flow velocity = liquid peaks + flow cavitation = wear. Particles enhance the effect! Risk of cavitation!

4. Considerable variations of product density: Sedimentation or floating. Fluids that tend to sedimentation can hardly be sucked in.

Remedy: Downflow Technology
In case of high viscosities (particularly with particles) it is essential to keep the deformation of the natural flow lines as little as possible. The higher the efficiency, the more gentle the pumping process because the entire energy loss is transferred to the fluid by means of the shearing effect.

Results: Pump wear, damage to the conveyed fluid!

Wear is regarded as indicator.
Oscillating Displacement Pumps
(Comparison Piston/Diaphragm pump)

Design Comparison

**Piston Pump**

*The conveyed fluid is in contact with sliding seals*

1. Pressure air vessel
2. Safety valve
3. Discharge valve
4. Suction valve
5. Suction air vessel
6. Conveyed fluid
7. Piston seal
8. Piston
9. Crank shaft
10. Diaphragm
11. Hydraulik oil
12. Plunger
13. Plunger seal
14. Crosshead

\[ V_L = \text{Leckagevolumen} \]

**Diaphragm Piston Pump**

*Hermetically sealed! The conveyed fluid is not in contact with sliding seals*

1. Pressure air vessel
2. Safety valve
3. Discharge valve
4. Suction valve
5. Suction air vessel
6. Conveyed fluid
7. Piston seal
8. Piston
9. Crank shaft
10. Diaphragm
11. Hydraulik oil
12. Plunger
13. Plunger seal
14. Crosshead

\[ V_M = V_K \text{ (theoretisch)} \]

Heinz M. Nägel 2016
Piston Pump/Diaphragm Pump Evolution

Schritt 1

Schritt 2

Schritt 3

Heinz M. Nägel 2016
Oscillating Displacement Pumps

*MULTISAFE* Double Hose-Diaphragm Pump

Second generation of Diaphragm Pumps
Working Principle of Double Hose-Diaphragm Pumps
Oscillating Displacement Pumps
Evolution of Hose-Diaphragm Pumps

Outlet

Piston

Inlet

Outlet

Flexible Hose

Piston

Hydraulic Liquid

Inlet
Oscillating Displacement Pumps
Evolution of Hose-Diaphragm Pump

Piston in rear position = End of suction stroke

Piston in front position = End of discharge stroke
Oscillating Displacement Pumps
Evolution of Hose-Diaphragm Pump

Inlet

Outlet

Housing

Hose Diaphragm

Piston

Pumped medium

Hydraulic liquid
Evolution of Pumps
Hose-Diaphragm Pump

- Hydrostatic pressure by surrounding hydraulic liquid
- Pressure inside and outside the diaphragm is equal
- Hose-diaphragm is not covering any pressure, except for static load
- Medium in contact with diaphragm only
Oscillating Displacement Pumps
Evolution of Hose-Diaphragm Pump

Hydraulic actuation of MULTISAFE hose-diaphragms

Initial situation

Maximum contraction during the discharge stroke
MULTISAFE Double Hose-Diaphragm Pump
(The internal Diaphragm is subjecting a excessive load)
Oscillating Displacement Pumps
Hose-Diaphragm (PTFE or Elastomer) Deformation

First typical shape of hose-diaphragm deformation

Second typical shape of hose-diaphragm deformation

Third typical shape of hose-diaphragm deformation
Double Hose-Diaphragm Pumps

Double Hose-Diaphragm

- Inner hose-diaphragm
- Layer of (unpressurised) water between the hose-diaphragms
- Outer hose-diaphragm

MULTISAFE
Hose-diaphragms are never stretched!
MULTISAFE® Double Hose-Diaphragm Pump

MULTISAFE Double Hose-Diaphragm and its Benefits
Double-hose diaphragm pump

- High filling efficiency due to intestine-like unique hose-diaphragm design
- Linear flow path without deviations
- Fast volume exchange in pump head, therefore
  - less sedimentation
  - no dead pockets

High efficiency

\[ \text{High efficiency} = \text{Less energy consumption and less wear} \]
MULTISAFE® Double Hose-Diaphragm Pump
Efficiency - Volume/Filling Ratio

Double hose-diaphragm pump

- Pump head volume is only 40% of a flat-diaphragm pump head
- 3 times higher filling ratio (pumped volume/max medium volume)

- Less weight
- Less width
- Compact gear box
- Higher efficiency
- Higher material flow in pump head
- Less sedimentation
- No dead pockets
MULTISAFE® Double Hose-Diaphragm Pump
(Working principle)

The working principle „Bionics in Pump Design“ is comparable with the human intestinal tract.
MULTISAFE® Double Hose-Diaphragm Pump Downflow Configuration

Triplex Double Hose-Diaphragm Pump

For chemically and mechanically aggressive, liquids and highly viscous media with various viscosities and consistencies and with dry solid content up to 80 %, depending on the medium, for different manufacturing industries

Flow rate: 0.1 to max. - Quintuplex Design - 1,000.00 m³/h
Pressure: max. 500 bar (depending on size)
MULTISAFE® Double Hose-Diaphragm Pump (Pumping of Slurry)

Mission impossible? Mission possible!
Mission impossible?  **Mission possible!**

15000 mPas
Oscillating Displacement Pumps

Suction behavior
Oscillating Displacement Pumps (Piston Pump)

Suction performance

When the piston of reciprocating pumps begins on its return stroke, the only force available to lift the self-acting valve and cause flow into the cylinder is the atmospheric pressure plus any static level of fluid in the suction pipe.

The safe suction lift depends on the pump design and can be recommended reliably only by the manufacturer of the pump.
Suction Behavior of Oscillating Pumps

The Net Positive Inlet Pressure [Pa]) head required by the pump is NPIPR (R: required). It describes which minimum net positive inlet pressure $\Delta p_i$ has to be overcome in the pump. To ensure that this pressure head can be overcome without cavitation, the suction system has to provide the NPSA (A: available) including a certain safety factor $S$ at the suction flange of the pump.

Therefore, the following generally applies: $SNPIPRNPIPA$ or $NPSHRNPSHA$. The minimum safety factor $S$ is 10% of the maximum vapor pressure.

The NPIPA considers

- the maximum of the sum of all pressure losses in the system
- the difference in height which has to be overcome
- the barometric pressure
- the vapor pressure $p_d$
- the container excess pressure $p_e$ and
- the flow velocity $v_B$ in the suction tank.
NPSH_A of the Plant

\[ \text{NPSH}_A = H_p + H_z - H_R - H_V - H_S \]

- \( \text{NPSH}_A \) m Holding pressure of the plant
- \( H_p \) m Pressure head of environment or tank
- \( H_z \) m Inlet head
- \( H_R \) m Head of friction and other flow loss
- \( H_V \) m Vapor pressure head
- \( H_S \) m Safety
Example of NPSH_A

- Ambient pressure (+10m)
- Inlet head (+3m)
- Friction loss (-2.5m)
- Vapor pressure (-1m)
- Safety (-0.5m)
- NPSHA (9m)
Variants and Multiplex Pumps

Suction Conditions: \( \text{NPSH}_A / \text{NPSH}_R \)

\[
\Delta p = \frac{\lambda}{\omega} \cdot L \cdot \frac{\rho^2}{d}
\]

\[
\Delta p = \zeta^2 \cdot \zeta.
\]

\[
\Delta p = \rho \cdot a \cdot L
\]

\( p_e, p_1, p_d \)

\( \zeta, \lambda, \zeta \)

\( \Delta p_m = \rho \cdot g \cdot L \)

\( S, \text{NPSHA}, \text{NPSHR} \)

Heinz M. Nägel 2016
Oscillating Displacement Pumps
NPSH (additional)
Classification into homogeneous and heterogeneous mixtures
Basic Consideration

Homogeneous suspension with high solids content

Fly & bottom ash (heterogeneous)

Heterogeneous mixture (settled)
Vertical upward delivery

In order to allow for the delivery of the particle, the sum of efficient forces has to feature a positive force component. Transportation forces counteract the settling speed of the solids.

At a flow velocity of the carrier fluid the solids are transported at the following speed:

$$w_K = w - w_s$$

In the event that the flow velocity of the carrier fluid \((w)\) falls below the settling speed of the particles \((W_s)\), sedimentation of solids will start.

---

**Symbols:**
- \(F_T\): Transportation force
- \(w_K\): Transportation speed of solids
- \(w\): Flow velocity of carrier fluid
- \(w_s\): Settling or sedimentation speed
- \(F_A\): Lifting force
- \(F_W\): Resistance power from circulation
- \(F_G\): Gravity

Heinz M. Nägel 2016
Diaphragm Piston Pumps
Diaphragm Failure Caused by Sedimentation

If the flow velocity of the carrier fluid falls below the settling speed of the particles, sedimentation of solids will start and cause a Diaphragm Failure.
Unique Modular Design for fluids with high differential density.

Traditional flow direction from the bottom to the top for fluids with lifting velocity, which is applied for products with floating tendency.

The unique DFT Technology (reversed pumping) is specified for products with specifically heavy particles in the carrier fluid that tend to settle and are accordingly difficult to be sucked in.
With DFT (Downflow Technology) the traditional pumping principle is literally turned upside down, which means that the flow is directed from the top to the bottom.

By this means, settling of solids within the pump can reliably be avoided.

The consistent modular construction system allows for individual adaptation, even on site.
MULTISAFE Double Hose-Diaphragm Pump
- Downflow Transport -

**Downflow Configuration**

For the handling of particularly heavy solids and heterogeneous mixtures.

Downflow Configuration = Flow from the top to the bottom of the pump

**Downflow (DFT) configuration** is the solution against sedimentation inside the pump.
Summery
Directions for pump selection and design

What kind of solids carrying fluids are to be handled?

Which requirements are to be met by the pumps?

Energetic and volumetric efficiencies are basic criteria for the suitability!

The higher the volumetric efficiency, the higher the energetic efficiency as well as flow and metering accuracy and wear resistance.

High noise level of the pump means that « it defends itself against application or service conditions » !

In case of high viscosities (particularly with particles) it is essential to keep the deformation of the natural flow lines as little as possible.

The higher the efficiency, the more gentle the pumping process because the entire energy loss is transferred to the fluid by means of the shearing effect.

Results : Pump wear, damage to the conveyed fluid !

With low viscosities, maximum energetic efficiency is achieved if the volumetric efficiency is likewise at maximum and internal leakage at minimum, respectively. Wear is regarded as indicator.
Cost pressure and the changing environmental awareness in process technology have significantly increased in the past few years.

As a consequence, demands for safety, efficiency, reliability, availability and diagnostics of the pumps have also increased considerably. These criteria are directly connected with the costs for production downtime, spare parts, service and maintenance.

The future challenges for pump manufacturers are rising, since the adaptation to the 4th Industrial Revolution (Industry 4.0/networking)/China 2025 and its consequences create assessment criteria will change a lot.

The technical and economic value and the traceable operating experiences will have a major influence on strategy and investments.
“Oscillating Displacement Pumps
Performance and Characteristics of positive displacement pumps”

Heinz M. Naegel, FELUWA

Many thanks for your attention

My reports are based on my longtime experience. I am convinced, that displacement pumps will become more and more important in a time of continuously increasing energy costs.