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PD Pumps, the Modern Solution for Pumping High Density Tailings

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Abstract

Hydraulic transport of solids is common in mining and processing. Mineral slurry pipelines transport products in an environmentally acceptable and economically efficient manner over long distances ranging from a few kilometres to several hundred kilometres. The first piston diaphragm pumps were introduced for pipeline service in the early 70’s for mineral ore transport applications such as OEMK in Russia and New Zealand Steel. For three decades, piston diaphragm pumps have enjoyed an ever-increasing popularity as a reliable, economic and environmentally friendly method to transport slurries. The technology has now matured into the industry standard pump technology for high pressure slurry pumping, backed up by the many successful installations world-wide.

From a disposal viewpoint it is no longer environmentally and economically acceptable to transport waste materials at low concentrations to large tailing ponds. Thickened tailings disposal systems and slope filling procedures are now actively sought and require much higher concentrations to be transported than can be delivered by conventional pipelines. Pumping systems for high concentration, fine particle suspension (paste) pipelines require different design than pumping systems for traditional slurry pipelines.

Due to the required increase in solids concentration and transport distance, piston diaphragm pumps have gained a substantial interest for thickened tailings applications. However larges flows have occasionally required an impractically large number of piston diaphragm pumps.

The development of the patented GLORES system (Geho LOad REduction System) has enabled the design of a triplex piston diaphragm pump with an unprecedented power rating of approximately 2800 kW allowing large flows.

This development had enabled a tailings system design with an acceptably, small number of pumps. The development of the largest pump diaphragm in the world and the use of numerical tools for the analysis of dynamic phenomena within the pump enabled a reliable pump design for the increased flow rate from a hydraulic perspective as well.

Introduction

There are many reasons for an increased interest in high concentration slurry transport systems. Environmental awareness is high on everybody’s agenda and the value of water as a sustainable resource is a key issue in many arid areas around the world. Ongoing developments in the field of thickening and filtration equipment have expanded the number of choices for high concentration systems (Gandhi, 2008). However, high concentration slurry pumping usually requires high discharge pressures. Practical limits are reached for the application of centrifugal pumps for high concentration pumping and Positive Displacement pumps (PD pumps) are more suitable for the high discharge pressures (Stephan, 1984; Venton, 1986; Lush, 1987; Rayo, 2009). Up to now, PD pumps have been excluded for large tailings projects due to flow limitations. The development of the patented GLORES system (Geho LOad REduction System) has enabled the design of a piston diaphragm pump with an unprecedented power rating allowing large flows. The increase in pump capacity was possible by the combination of GLORES, with continuous incorporation of field experiences of operating pumps in newer designs, conservative design and selection guidelines and in-depth research and development using numerical modelling techniques, combined with experimental research for verification.

Piston diaphragm pump design and selection

Many design and selection choices have to be made, starting from the initial project requirements, which are defined by the concentration and mass flow rate of solids to be transported. In order to specify the flow rate and pressure requirements for the pumping system, the solids concentration and slurry rheology have to be determined also. Centrifugal, hydraulic driven piston, crankshaft driven piston and piston diaphragm pumps are all used for tailings pumping. This requires that a comparison of capital and yearly operating costs for different pumping systems is made. The use of PD slurry pumps enables pumping of slurries with high solids concentration and viscosities which requires higher discharge pressures, but lower flow rates for a given transport problem. From a total cost of ownership perspective, piston diaphragm pump are preferred as these pumps have very high efficiencies and a low number of wear parts, resulting in low operating cost compared to other PD pump technologies and to centrifugal pumping (Holthuis and Simons, 1980, 1981; Beekman, 2004; Kuenen, 2008; Simons, 1987; van Rijswick, 1991). Currently, for red mud or other high density mine tailings disposal systems, the PD pump technology permits tailings transport in near-paste conditions which enables a dry stacking type of tailing disposal (Kuenen, 2008). Pumping tailings at proper consistency ensures optimal spreading at the disposal area with a small angle of repose and very smooth surface. This approach is preferred over mechanical spreading because of the smooth surface rainwater can run off at low velocity so that no erosion gullies are created. Wet climate conditions are additional motivations to select high concentration slurry disposal by pumping (Kuenen, 2008) instead of trucking.

Critical evaluation of different pump technologies is crucial for the design of an optimal slurry transport system. The selection of different pump technologies results in quite different possibilities regarding solids concentration, rheology, flow rate and discharge pressure for a given transport problem.

Duplex double acting and triplex single acting piston diaphragm pumps

Before indicating the design and selection variables for the piston diaphragm pump, its operation is explained first

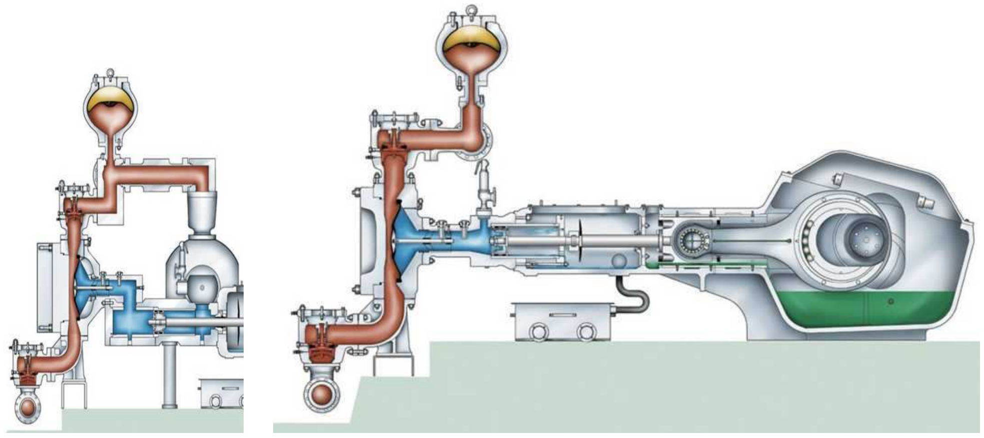


Figure 1: Cross section of a GEHO double (left) and single (right) acting piston diaphragm pump

In Figure 1 a crank mechanism is shown which generates a reciprocating motion of the piston via the piston rod in which the so-called rod load, F_{rod}, is present. This piston displaces a hydraulic fluid, called the propelling liquid, which displaces a rubber diaphragm in the pump chamber. When combined with self acting non-return valves in the suction and discharge manifold, a positive displacement pump action is generated. As the flow is generated by a more or less sinusoidal motion of the piston, a flow pulsation is present which is damped by a volume absorbing device such as a gas filled accumulator. The main benefit of the piston diaphragm pump for slurry applications is the reduced number of wear parts compared to other PD pump technologies such a piston and plunger pumps. In double acting pumps the piston displaces fluid on both sides and drives two pump chambers. This almost doubles the flow rate per piston when compared to a single acting pump in which the piston only displaces fluid on one side of the piston.

In addition to the single or double acting nature, a variation in the number of pistons is possible. The nomenclature from the Hydraulic Institute (ANSI/HI 6.1-6.5-1994, 1994) for reciprocating pumps is also used for the identification of piston diaphragm; the first part of the name identifies the number of cylinders, or subsequently; simplex, duplex, triplex, quadruplex, quintuplex, etc., followed by the single or double acting nature of the piston. In the GEHO piston diaphragm pump line, two types dominate; the triplex single acting and the duplex double acting piston diaphragm pump.

The economic evaluation should be based on both capital costs and on operational costs which include maintenance costs, wear parts costs and energy costs. This evaluation generally states that the use of fewer larger components or machines is more cost effective than the use of smaller components or machines.

Triplex single acting versus duplex double acting piston diaphragm pumps

In the previous Section both the triplex SA as well as the duplex DA pumps have been described. The main advantages of the duplex DA over the triplex SA piston diaphragm pump can be summarised as follows:

- More cost effective power end design because of the two cylinder DA design versus three cylinder SA design.
- Higher available pump power for a given maximum rod load and stroke length.
- Unloading of the power end by higher suction pressures (suction pressure on one piston side decreases the rod load generated by the discharge pressure on the other side of the piston, see Figure 1).

The advantages of the triplex SA over the duplex DA piston diaphragm pump can be summarised as follows:

- Lower flow pulsations, approximately a factor two. This is a specific consequence of the single versus double acting operating principle (van Rijswick, 2007). A triplex single acting PD pump therefore requires a much lower dampening volume, approximately a factor 5, and therefore generally has lower pressure pulsations.
- Lower number of pump chambers, three for triplex SA versus four for duplex DA:
  - The smaller number of larger size pump chambers results in a more cost effective liquid end, especially in case of special material requirements.

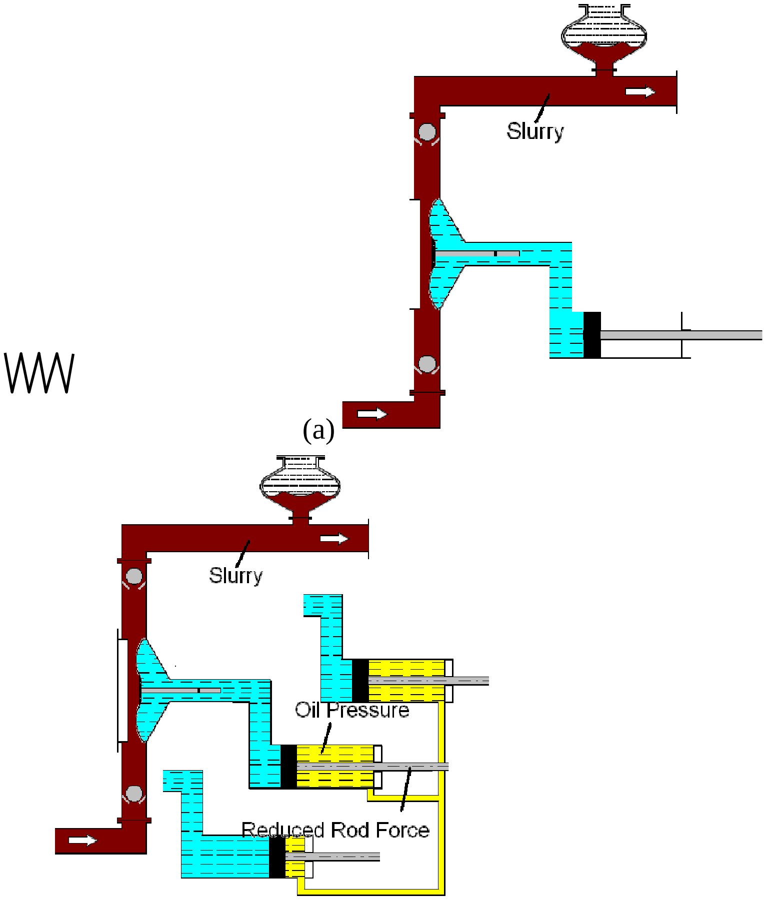
  - The lower number of wear parts compared to four or five cylinder results in a higher pump reliability as the probability of failure is reduced, which is especially important in abrasive slurry pumping.
  - The lower number of wear parts results in lower maintenance costs.
- Lower torque fluctuation. Similar to the flow pulsation, the torque fluctuation of the triplex SA pumps is approximately 50% of that of a duplex DA pump. This lowers the requirements for the pump drive, especially for the gear box and frequency converter.
- Lower mechanical unbalances. As the three crank journals of a triplex single acting PD pump are uniformly phased at 120°, compared to the two non-uniformly 90° phased crank journals of the duplex double acting PD pump, much lower mechanical unbalances result. For small size, and low speed pumps these unbalanced loads can be neglected compared to the weight of the pump but for the larger and higher stroke rate pumps these unbalanced loads should be included in the foundation design.
- By parallel pumping of several triplex pumps in combination with a-synchronisation of drive unit a 6, 9, 12 or 15 – cylinder installation is created. This makes it possible to equalize the typical pulsations of PD pumps.

Glores

As described in the previous section the triplex SA piston diaphragm pump is preferred over the duplex DA piston diaphragm pump from liquid end and dynamic perspectives. The duplex DA piston diaphragm pump however, is more cost effective from a power end perspective and allows the selection of a higher power and/or flow rate per pump for a given maximum rod load and pump chamber volume respectively. In order to combine the benefits of the duplex DA and triplex SA piston diaphragm pump, WEIR Minerals Netherlands has developed and patented a load reduction system called GLORES for single acting piston diaphragm pumps. GLORES greatly reduces the load on the pump power end thereby increasing the power rating of a specific power end. This enables the selection of a more cost effective single acting power end for a given application or a lower number of higher power pumps for high power applications.

The pump chamber pressure variation in time can be approximated by a square wave; during the suction stroke the pressure is equal to the suction pressure and during the discharge stroke it is equal to the discharge pressure. This pump chamber pressure is transferred into the rod load via the surface area of the piston, which therefore can be approximated by a square wave as well, as shown in Figure 4 by F_{piston}. The rod load generated by the discharge pressure is high during the discharge stroke of a single acting PD pump, but low during the suction stroke as the suction pressure is normally negligibly small compared to the discharge pressure. The power end components in a single acting PD pump are therefore only loaded during 50% of the crankshaft revolution.

The concept of GLORES is based on storing energy during the suction stroke by additionally loading the piston in opposite direction which is subsequently used to assist the piston in the discharge stroke. This concept is best explained by Figure 2a, in which a piston is shown which is loaded by a mechanical spring on the back side of the piston. During the suction stroke of the piston shown in Figure 2a, energy is stored in the spring which is released during the discharge stroke. The spring load increases the piston rod load during the suction stroke, in opposite direction of the pressure load in the pump chamber, but lowers the piston rod load during the discharge stroke. Although this spring analogy works well for explaining the basic concept of GLORES, it is not considered to be a practical solution for rod load balancing. For a piston diaphragm pump hydraulic oil is used as intermediate liquid between the piston and pump diaphragm. GLORES system also makes use of this existing hydraulic oil system for load balancing. The backside of the piston is loaded by a constant hydraulic pressure instead of a spring load. In a simplex power end, a large volume absorbing device would be required in order to absorb the swept volume of the piston while maintaining a constant pressure. In a multi cylinder pump it is possible however to connect the backsides of the individual cylinders allowing the hydraulic fluid to flow from one cylinder to the other during the crankshaft revolution as is shown in Figure 2.



(a)

(b)

Figure 2: GLORES concept: (a) Spring analogy, (b) Triplex SA with hydraulic load balancing

When the piston phasing is uniformly distributed across the crankshaft revolution the theoretical volume fluctuation in the balancing circuit is zero. This allows the design of a very compact hydraulic balancing circuit without the need for large volume absorbing devices. The effect on the piston rod load is shown in Figure 3.

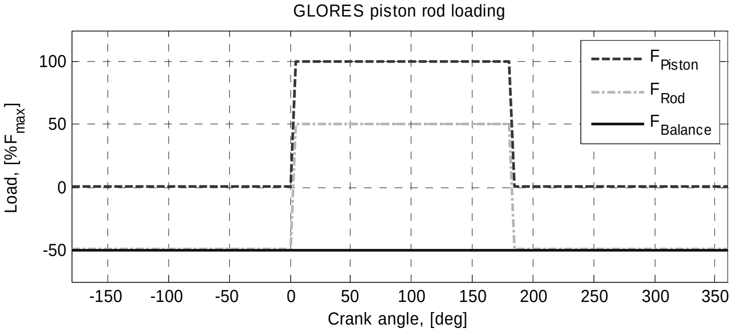


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Figure 3: Rod load with and without GLORES

The rod load shown in Figure 3 is normalised to the maximum hydraulic load on the piston generated by pump chamber pressure. For simplicity, the chamber pressure during the suction stoke is assumed to be zero. In the single acting piston diaphragm pump without GLORES, the rod load is equal to the piston load, F_{Piston}, which is fluctuating between 0 and 100%. When GLORES is enabled, a hydraulic pressure is applied to the backside of the piston which generates the balancing load, $F_{Balance}$, which is the average of the rod load during the suction and discharge stroke, in this case 50%. The result is that the rod load seen by the power end, F_{rod}, changes from a 0 to plus 100% fluctuation to a minus 50% to plus 50% fluctuation. The amplitude of the rod load is not changed but the maximum load level has been reduced by a factor 2.

When GLORES is enabled, both tension and compression rod loads are present at the same time in different piston rod which has a very beneficial effect on the bending moment of the crankshaft, which is reduced approximately a factor 3 as can be seen in Figure 4. This has a very beneficial effect on the crankshaft bending stress and deflection, eliminating any requirement for intermediate bearings. The driving torque and its fluctuation in time remain unaffected by GLORES as the GLORES balancing loads, $F_{Balance}$, requires no driving torque as they are balanced within the power end by the uniform piston phasing.

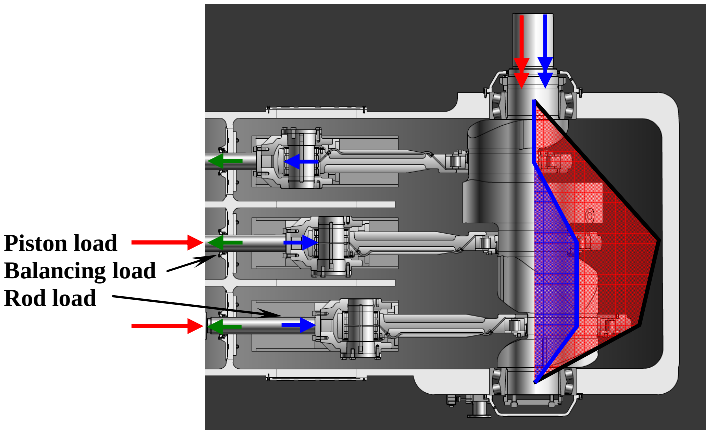

Figure 4: Bending moment on triplex SA crankshaft with and without GLORES

The roller bearing loads are reduced by a factor 2 as well, but the duty cycle of this load changes from 50–100%. The effect on bearing life can be evaluated using the equivalent load calculation according (ISO 281:2007, 2007) shown in Equation (1).

1.

$$F_{eq} = \sqrt[c]{\frac{T_{suc} \cdot F_{suc}^{c} + T_{dis} \cdot F_{dis}^{c}}{T_{suc} + T_{dis}}} \Rightarrow$$

$$L_{10h} = \frac{10^6}{60 \cdot rpm} \cdot \left(\frac{C_{dyn}}{F_{eq}} \right)^c \qquad \textbf{(1)}$$

With a load exponent c = 10/3, this gives a reduction of the equivalent bearing load of a factor 1.6, or when expressed in bearing life, an increase bearing life of a factor 5.

The GLORES system is particularly suited for piston diaphragm pumps as it uses the already available propelling liquid for the load balancing. The pressure control of the GLORES system is integrated within the existing pump controller.

The development project within Weir Minerals Netherlands involved the construction of a full scale prototype pump which has been subjected to testing for evaluation of the GLORES performance and fine tuning of the system. This testing included strain gauge measurements on the piston rod. The results of some stain gauge measurements are shown in Figure 5 where one can see that the piston load is fluctuating between approximately 0 kN and 710 kN as calculated from the pump chamber pressure measurement. The balancing load is a more or less constant load at approximately 355 kN, calculated from the GLORES balancing pressure measurement. The resulting rod load initially fluctuates between -355 kN and +355 kN as calculated from the stain gauge measurement. After approximately 10 seconds the GLORES pressure control is deliberately disabled in order to show the rod load approaching the piston load. At approximately 35 seconds the GLORES pressure control is enabled again showing the increase in balancing load which balances the rod load again around a zero mean value.

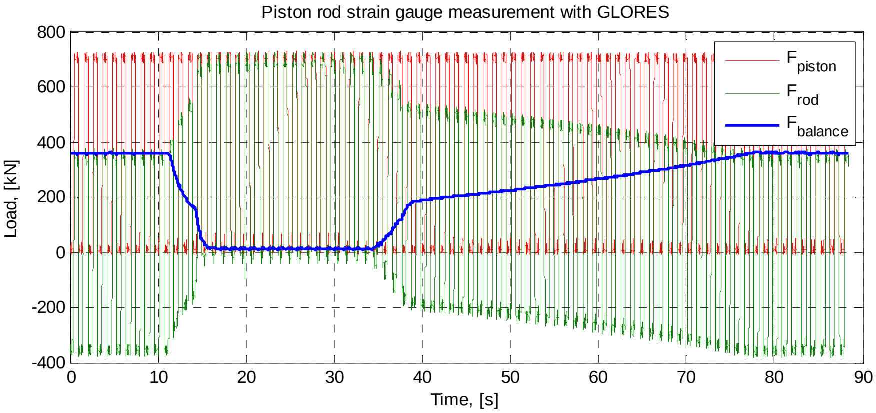

Figure 5: Strain gauge measurements on piston rod of GEHO pump with GLORES

Some components also required a re-design in order to make them suitable for the bi-directional loading condition. The re-design for the bi-directional loading is based on the design rules which are proven in the double acting pumps, in which the rod load is of bi-directional nature as well.

Reviewing the advantages of the duplex DA and triplex SA piston diaphragm pumps, one can see that all the advantages of the triplex pump are maintained, while the first three advantages of the duplex pump are superseded; a triplex SA power end with GLORES is more cost effective than a duplex DA power end and the available power for a given maximum rod load is higher a well. The unloading of the power end in case of higher suction pressures can be obtained using GLORES when the balancing load is the average of suction and discharge load on the piston. The theoretically higher flow rate capacity of a duplex DA piston diaphragm pump for a given maximum pump chamber size remains. However in the next section it will be shown that, especially for high volume applications, the triplex SA piston diaphragm pump is preferred above the duplex DA piston diaphragm pump.

Scaling laws in pump dynamics

As described in Section "Gloris“ GLORIS significantly increases the power rating of single acting power ends. This enables the design and selection of piston diaphragm pumps with much higher flow rates than before. This requires increasing the liquid end modules as well. This increase however, is not just simply increasing the size of these modules. While increasing the size of these liquid end modules, several dynamic aspects become important to consider in the design and selection of the piston diaphragm pump which are less important in smaller pumps. This is a result of the laws of scale that hold for the diverse dynamic aspects. Some of these aspects can be grouped as follows:

1. Valve dynamics: the motion of the valves is driven by the force balance on the valve body which incorporates valve inertia, valve weight, spring load, valve pressure drop and valve drag. The portion of the valve drag in the force balance increases for increasing valve size which can result in large valve closing delays when not properly predicted and compensated. The valve opening influences the maximum particle size which can pass but also the flow velocities in the valve gap, the latter being important for the erosion wear of the valve housings. Weir Minerals Netherlands has developed numerical models in order to predict the dynamic behaviour of the valves.

2. Pressure dynamics: the increased importance for proper pressure pulsation control for larger systems is explained in Bullet 1.

3. Diaphragm deformation: the diaphragm deformation is caused by fluid forces acting on the diaphragm which are not always symmetric. In small piston diaphragm pumps the asymmetric fluid forces can be neglected and only a symmetrical volumetric displacement of the diaphragm is present. In larger piston diaphragm pumps however, the asymmetrical diaphragm deformation has to be included in the design and selection of the pump. The asymmetric fluid forces generate increased strain levels in the diaphragm material. As the diaphragm is flexed every stroke of the pump, approximately 30×10^6 times a year in a continuous 8,000 h/year service, early diaphragm fatigue failures can result when the strain levels are not kept below some limit. Incorrect prediction of these asymmetric forces and resulting strain levels can be the difference between a GEHO diaphragm life of 8,000–20,000 hours or only a few hundred hours. If diaphragm life is only a few hundred hours, a double or even triple diaphragm design will not improve the situation. Premature failure should be avoided by design instead of trying to compensate by a second or third diaphragm. Weir Minerals Netherlands uses diaphragm selection guidelines which are based on detailed analysis of the strain levels in the GEHO diaphragm with non-linear finite element models which are combined with almost 40 years of operational experience with GEHO PD pumps in slurry applications.

All these aspects incorporate specific laws of scale which have to be included for a reliable pump design. It is beyond the scope of this paper to describe all the laws of scale in detail. In Bullet 1 some details and some results of numerical models regarding pressure dynamics will be given. All the models have been verified experimentally, some of this verification is described in van Rijswick (2007).

Pressure dynamics

The increased pump capacity, which is enabled by GLORES, requires additional focus on pressure dynamics. Crankshaft driven PD pumps inherently generate a non-constant flow. In order to attenuate this flow pulsation, volume absorbing devices or pulsation dampeners are generally used on these pumps. As already mentioned triplex SA positive displacement pumps generate much lower flow pulsations than duplex DA positive displacement pumps. For an equal pressure pulsation level a duplex DA pump requires more dampening volume. This is not always feasible; hence duplex DA pumps generally tend to have higher pressure pulsation levels than triplex SA pumps. For higher flow rates, triplex SA piston diaphragm pumps equipped with GLORES are therefore preferred above duplex DA piston diaphragm pumps.

Appropriate pressure pulsation control is more important for high volume applications, as the pressure pulsations create unbalanced loads in the piping which are proportional with pipe cross sectional area (van Rijswick, 2007). The unbalanced loads can result in pipe vibration when the piping is not properly supported. In small systems appropriate pipe support is not an issue and in case of high vibration levels it is relatively easy to add additional supports. In high volume applications with large pipe diameters the unbalanced loads can be of considerable magnitude such that appropriate pipe support is no longer feasible or requires expensive supports with massive foundations when the pressure pulsations are not sufficiently controlled.

Conclusions

This paper described the developments which enabled the design of GEHO piston diaphragm pumps for high capacity applications:

- Development of GLORES, a load balancing system for single acting piston diaphragm pumps which significantly increases the power rating of triplex single acting power ends.
- Power end component design for bi-directional loading in GLORES equipped triplex single acting piston diaphragm pumps is based on existing technology of double acting pumps, while maintaining the benefits of the liquid end of triplex single acting piston diaphragm pumps.
- The increased power rating by GLORES allows the selection of a smaller number of pumps in high volume pump stations which minimises capital as well as operational costs while maintaining a high reliability.
- As GLORES increases the power rating of a pump, much higher flow rates per pump are possible which poses several specific challenges on the pump liquid end from a dynamic perspective. Based on experimentally verified numerical models the following developments enabled a reliable pump design from a hydraulic perspective:
- Optimum valve design for balancing wear and valve dynamics
- Improved pulsation dampener layout in order to limit high frequency pressure pulsations
- Pump synchronisation in order to exclude the excitation of interaction resonances in multi pump installations with dramatic decrease of pump station pressure pulsation level
- Development of the world largest pump diaphragm.

These developments enable the use of piston diaphragm pumps in high volume application such as large red mud, iron or copper tailings systems, large concentrate pipelines, larger flow digester feed or oil sands disposal applications.

Table 1: List of symbols

Symbol	**Unit**	**Description**
F	N	Force
Rpm	min^{-1}	Speed
T	s	Time period
C	-	Load exponent
L_{h10}	h	Nominal bearing life
C_{dyn}	N	Dynamic load rating

References

ANSI/HI standard 6.1-6.5-1994 (1994) Reciprocating Power Pumps, Hydraulic Institute, 9 Sylvan Way, Parsippany, NJ 07054-3802, ISBN 1-880952-10-6

Beekman, T. (2001) Different Pumptypes for Tailings, a Selection Guideline, High Density & Paste 2001, 10-11 May, 2001, Seminar - Pilanesberg, South Africa

Gandhi, R., Weston, M., Talavera M., Brittes, G.P., Barbosa, E., Design and Operation of the World's First Long Distance Bauxite Slurry Pipeline, Light Metals 2008, Volume 1, Aluminum and Bauxite, page 95-100, edited by D.H. De Young, The Minerals, Metals & Materials Society, March 2008

Holthuis, C.H. and Simons, P.W.H. (1980) The GEHO diaphragm pump, A new generation of high-pressure slurry pumps, Hydrotransport 7, Sendai, Japan, BHRA Fluid Engineering and Slurry Transport Society of Japan, November 4-6, 1980, ISBN 0 906085 46 2, page 17-32

Holthuis, C.H. and Simons, P.W.H. (1981) The economics of positive displacement slurry pumps, in Proceedings 6th International Technical Conference on Slurry Transportation, Las Vegas, Nevada, USA, ISBN 0-932066-06-2 65, page 156-161

ISO standard, ISO 281:2007 Rolling Bearings – Dynamic load ratings and rating life, International Organization for Standardization, 2007

Kuenen, J. (2008) Pumping and Storage of Bauxite Processing and Power Generation Residues, Xth Congress of ICSOBA-2008, Bhubaneswar, India, International Committee for Study of Bauxite, Alumina & Aluminium, 28-30 November 2008, Page 242-253

Lush, S.M. and Pope, P.B. (1987) The New Sealand Steel ironsand slurry pipeline, Proceedings of the 12th International Technical Conference on Slurry Technology, March 31 – April 3, 1987, New Orleans, Louisiana, USA, published by Coal and Slurry Technology Association, Washington DC., 1987. ISBN 0-932066-12-7 125

Rayo, J., Fuentes, R. and Orellana, R. (2009) Large tailing Disposal – Conventional versus Paste, in Proceedings 12th International Seminar on Paste and Thickened Tailings (Paste09), R. Jewell, A.B. Fourie, S. Barrera, J. Wiertz (eds), 21–24 April 2009, Viña Del Mar, Chile, Gecamin Limited, Santiago, Australian Centre for Geomechanics, Perth, pp. .

Simons, P.W.H. (1987) Große Membranpumpen für abrasive Slurries, Pumpen, 1. Ausgabe,Vulkan Verlag, Essen, 1987, ISBN 3-8027-2670-7

Stephan, F. and Navrade, D.H. (1984) Experiences during the commissioning of the iron concentrate pipeline at O.E.M.K/USSR, in Proceedings 9th International Technical Conference on Slurry Transportation, Lake Tahoe, Nevada, USA, Slurry Technology Association, 1800 Connecticut Avenue, N.W. Washington. ISBN 0-932066-09-7 75, page 175-184

van Rijswick, G. (1991) Förderung von Slurries mit Hilfe von Membranpumpen, Pumpen, 2. Ausgabe, Vulkan Verlag, Essen, ISBN 3-8027-2696-0 van Rijswick, R. (2007) Pressure pulsation analysis of crankshaft driven positive displacement pumps, Hydrotransport 16, Cape Town, South Africa, 7-11 May 2007, page 219-230, Symposium organised by The Southern African Institute of Mining and Metallurgy and the BHR Group

Venton, P.B. and Cowper, N.T. (1986) The New Zealand Steel ironsand slurry pipeline, Hydrotansport 10, Innsbruck Austria, BHRA, The Fluid Engineering Centre, Cranfield, Bedford, UK, ISBN 1-85166-065-X page 237-246