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EFFECT OF PARTICLE POROSITY ON PUMP HEAD REQUIREMENTS FOR PHOSPHATE ORE SLURRY DISTRIBUTION PIPELINES AT THE JORF LASFAR TERMINAL FACILITIES IN MOROCCO

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The total dynamic heads (TDH) across either two or three identical centrifugal pumps in series were estimated for 50%, 58% and 60% by mass phosphate ore slurry concentrations for two of the ten ore slurry distribution pipeline layouts at the Jorf Lasfar terminal facilities in Morocco. The two pipeline internal diameters used were 182.5 mm and 285.7 mm. The TDH was calculated using frictional pressure gradients for pipeflow assuming a segregating slurry and estimated using the Saskatchewan Research Council (SRC) 2007 Two-Layer PipeFlow model for heterogeneous flow in horizontal pipes. The model was also used to check that the proposed pipeline operating velocities always adequately exceeded the predicted deposition velocity for the operating conditions examined. The effects on the TDH calculations of three different ore particle porosities (9.5%, 20% and 30% v/v) for 50%, 58% and 60% by mass ore concentrations were assessed for several dry ore throughputs. It was found that the assumed value of the ore particle porosity over the range of 9.5% to 30% v/v is relatively unimportant compared with the effects of the ore concentration and dry ore solids throughputs.

KEY WORDS: Phosphate slurry, pipeline design, pumps, particle porosity and size distribution.

1. INTRODUCTION

Phosphate mines and beneficiation facilities at Khouribga in Morocco, a slurry transportation system (Ref. 3), and terminal facilities at Jorf Lasfar, have all been developed to increase phosphate production. These facilities include the pipeline terminal station at Jorf Lasfar to receive slurry from the main 187-km long distance pipeline and divert it to local process plants, and to process facilities to prepare the phosphate for local use and for export.

Figure 1 shows some the ore slurry distribution pipelines. A previous BHR Group study (Ref. 1) considered the hydraulics of three of the ten distribution pipelines. This paper describes estimation of the total dynamic head (TDH) required for two of the ten distribution pipelines from feed tanks to processing plants. Two pipelines of internal diameter 182.5mm (P5 pipeline) and 285.7mm (MP3 pipeline) have been selected, and previously described (Ref. 1). In the first case, two equally-sized centrifugal slurry pumps were used in series and in the second case three pumps in series were used.

Various phosphate ore throughputs have been used for these calculations in combination with ore slurry concentrations of 50%, 58% and 60% w/w. The ore throughputs correspond to the minimum, the normal operation, and the process guarantee values as specified by the client. A single ore particle size distribution was assumed and particle porosities of 9.5%, 20% and 30% were used throughout. The frictional pressure gradient and therefore TDH were estimated assuming the slurry is transported in the heterogeneous flow regime in horizontal pipework.

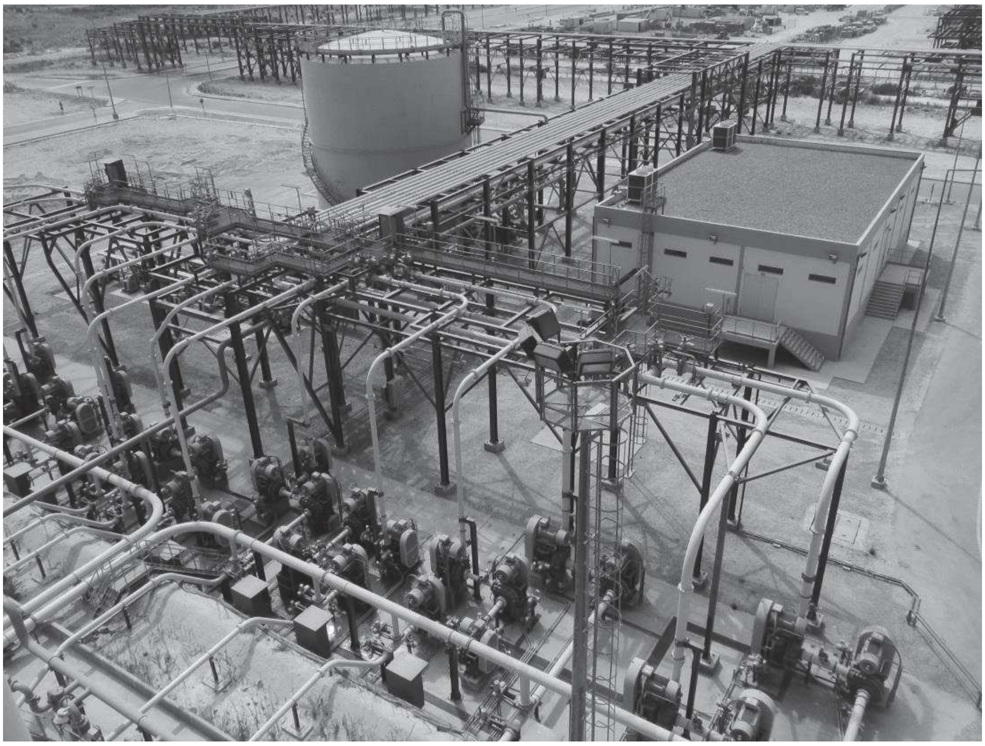

Fig. 1 Ore slurry distribution pipelines at the Jorf Lasfar terminal facilities in Morocco

2. PHOSPHATE ORE PARTICLE AND SLURRY PROPERTIES

2.1. PARTICLE POROSITY

An initial average particle porosity of 20% by volume was assumed for the basic engineering design of the slurry pipelines. However, there was some significant uncertainty in this figure and so two other porosities of 9.5% and 30% were used to see how the variation in assumed particle porosity may affect the TDH estimations. 9.5% was chosen as the arithmetic average of values obtained through testwork in the USA (Ref. 2) which involved mercury intrusion and gas adsorption porosimetry The former technique gave a value of 7.52% from an average from 3 samples, and the latter 11.4%.

2.2. PARTICLE SIZE DISTRIBUTION (PSD)

The PSD used for hydraulic is shown in Figure 2.

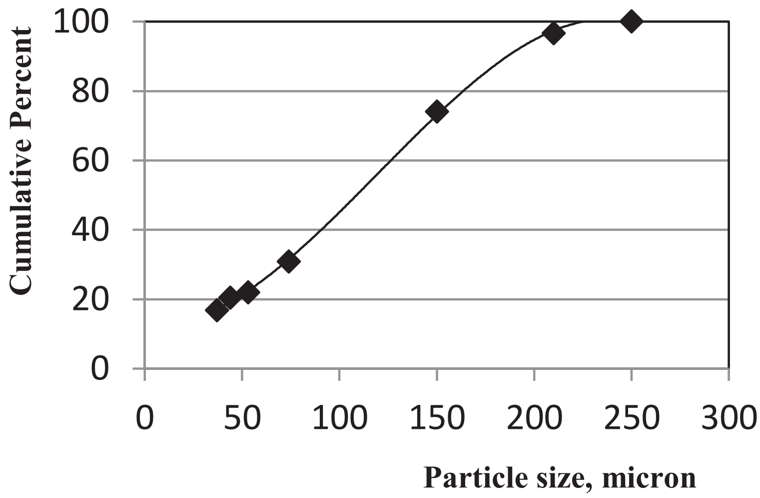

Fig. 2 Ore particle size distribution

2.3. SLURRY DENSITIES

The three phosphate ore concentrations investigated corresponded to slurry densities of 1500 1630 and 1667 kg/m³. The SRC 007 Two-Layer model for hydraulic design (see Section 3.1) requires the proportion of particles below 74 microns and also the slurry densities of the "fines" fractions. This proportion is 0.308 and forms the carrier fluid with the water in which the "coarse" solids are suspended. The proportion of "coarse" particles is 0.692. Table 1 summarises the calculation of the carrier fluid density for a 20% v/v ore particle porosity in terms of the overall slurry concentration. Similar calculations were carried out for the 9.5% and 30% particle porosities.

Table 1

Calculation of carrier fluid density (based on 1 m³ of phosphate ore slurry)
Assuming a 20% particle porosity

Slurry concentration, % w/w on dry solids basis	50	58	60
Volume of solids, excluding pores, m³	0.250	0.315	0.333
Volume of water, m³	0.750	0.685	0.667
Volume of solids with 20% pores	0.313	0.394	0.417
Volume of "free" water, m³	0.688	0.606	0.583
Density of solids no pores, kg/m³	3000	3000	3000
Density of particles with 20% pores containing water, kg/m³	2600	2600	2600
Density of carrier fluid, kg/m³	1196	1267	1289

3. HYDRAULIC DESIGN OF PIPELINES

3.1. SRC TWO-LAYER MODEL

The SRC Two-Layer 2007 model assumes that the slurry is segregating under gravity. The model assumes a constant velocity and solids concentration across the cross-section in two hypothetical upper and lower layers, and concentration and velocity variations within these layers are neglected A broad particle size distribution is dealt with assuming that <74 micron solids ("fines") are distributed uniformly across the pipe cross-section and relevant fluid parameters, such as density and viscosity, are based on the "fines", rather than on the liquid phase. The viscosity of the "fines" fraction was estimated using the SRC predictive equation.

The >74 micron solids represent the "coarse" slurry. From the ore particle distribution, the d_{50} of the coarse fraction (>74µm) was estimated to be 0.130mm. A further parameter in the modelling of the slurry pipe flow is the maximum packing fraction of the coarse solids (> 74 microns), by volume. This is a measure of the maximum packing that the solids can achieve, and is often estimated through gravity settling tests using slurry samples placed in a graduated cylinder. This was carried out three times, using process water, local tap water and distilled water. The average value obtained and used was 0.50. The coefficient of sliding, Coulombic friction between coarse solids and the pipe wall was assumed to be 0.5.

Checks were also made that the operating velocity was always significantly in excess of the predicted deposition velocity.

3.2. CALCULATION OF TOTAL DYNAMIC HEAD (TDH)

On the suction side of the first pump of two pumps in series, total pressure loss is given by

$$P_{suction} = P_{ss} - P_{vh} - P_{fs} - P_{ffs} \tag{1}$$

where P_{ss} is the pressure relating to the static head of the slurry in the feed tank

P_{vh} is the pressure relating to the velocity head at the pump suction flange.

P_{fs} is the frictional pressure loss in the suction line

P_{ffs} is the frictional pressure loss across fittings in the suction line.

On the discharge side, downstream of the second pump for the P5 pipeline (or third pump for the MP3 pipeline) in series, the total pressure loss is by

$$P_{discharge} = P_{fd} + P_{ffd} + P_{sd} \tag{2}$$

where P_{fd} is the frictional pressure loss in the discharge line

P_{ffd} is the frictional pressure loss across fittings in the discharge line.

P_{sd} is the pressure relating to the static head of the slurry.

The frictional pressure loss across fittings in pipework is given by

$$P_{ff} = \frac{1}{2}\rho V^2 \sum K_{fitt} \tag{3}$$

where ΣK_{fitt} is the summation of all the K_{fitt} values for the fittings.

The total differential head is then given by

$$TDH = \frac{\left(P_{discharge} - P_{suction}\right)}{\rho_m g} \tag{4}$$

4. TDH PREDICTIONS FOR DISTRIBUTION PIPELINES

4.1. P5, 182.5 MM ID DISTRIBUTION PIPELINE

Figure 3 shows the P5 pipeline layout and Figure 4 is a plot of the predicted total dynamic head (TDH) in m slurry over the two similarly-sized centrifugal pumps as a function of the three ore particle porosities. TDH values are given for the three ore concentrations of 50%, 58% and 60% by mass, and at the two lowest and highest dry ore throughputs of 170 and 240 t/h. As expected, the predicted TDH is much higher for the lowest ore concentrations of 50% and at the higher dry ore throughput of 240 t/h, but the effect of the assumed ore particle porosity is small. The relative unimportance of a wide variation in the ore particle porosity is probably because although larger particle porosities result in higher solids volume fraction than smaller ones, at a given ore concentrations by mass, and this would tend to increase the frictional pressure gradients and therefore the TDH, large porosities also reduce the particle density which would tend to reduce TDH.

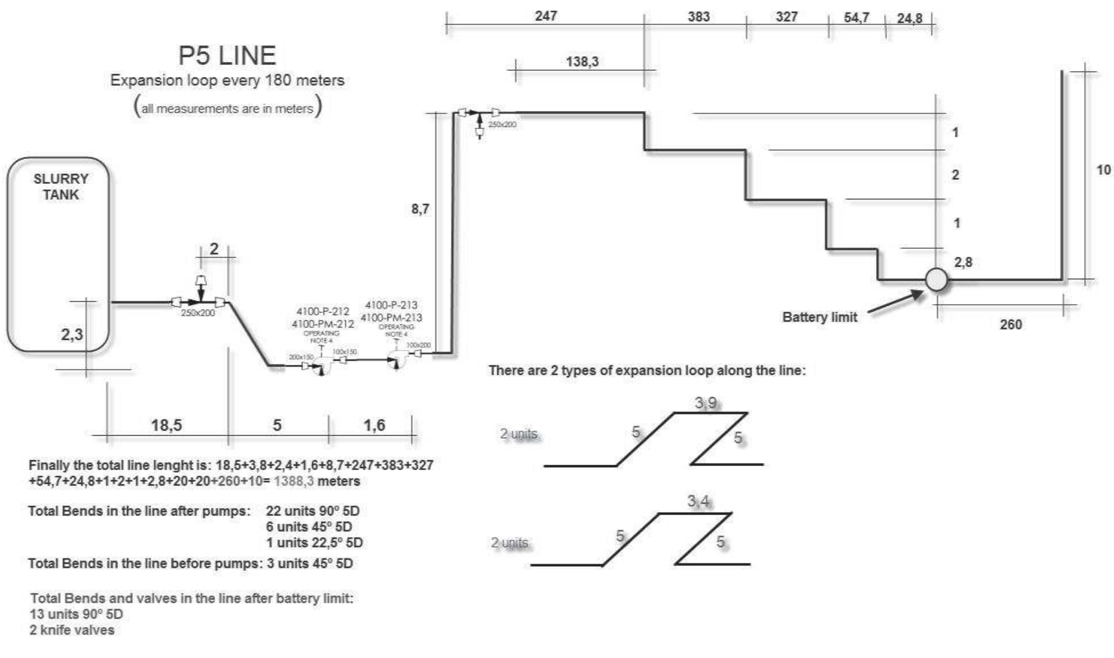

Fig.3 P5 ore slurry distribution pipeline, showing two geometries for the expansion loops

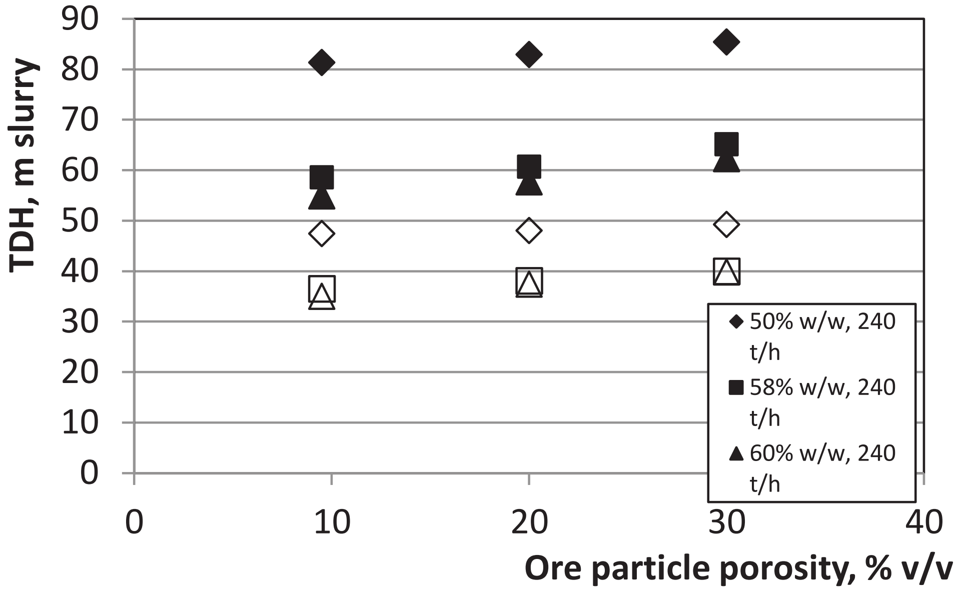

Fig. 4 Predicted TDH for the P5 pipeline at 20^{0}C using the SRC 2007 PipeFlow model only

4.2. MP3, 285.7 MM DISTRIBUTION PIPELINE

Figure 5 shows the layout of the MP3 pipeline.

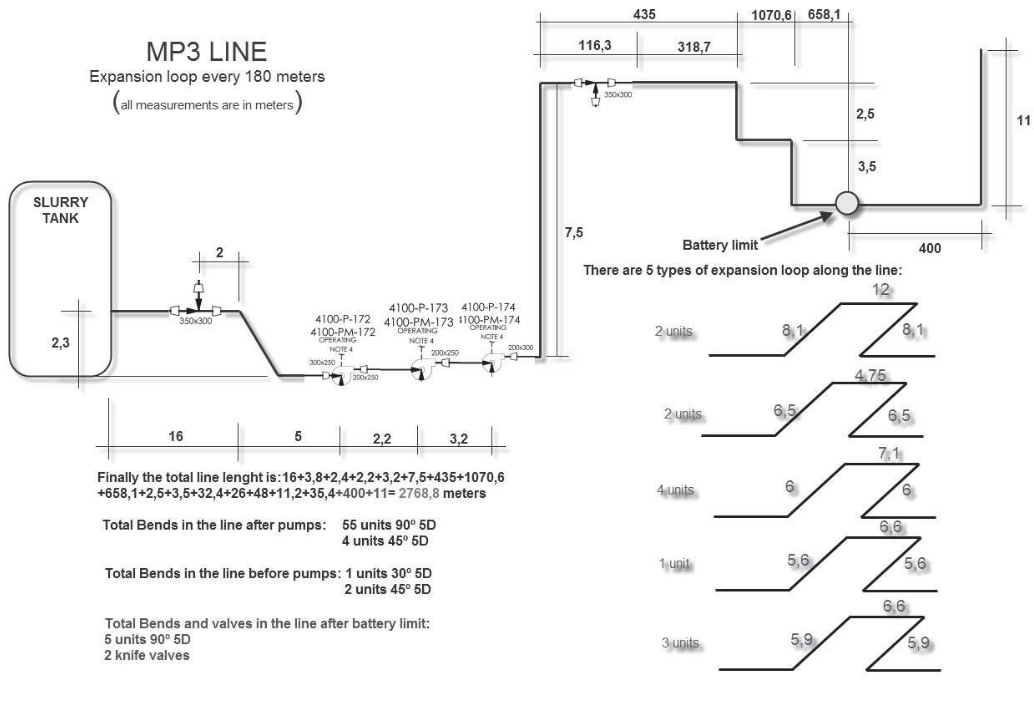

Fig. 5 MP3 ore slurry distribution pipeline showing five designs for the expansion loops

Figure 6 is a plot of the predicted total dynamic head (TDH) in m slurry over the three similarly-sized centrifugal pumps for the MP3 pipeline as a function of the three ore particle porosities. TDH values are given for the three ore concentrations of 50%, 58% and 60% w/w and at the two smallest and largest two dry ore throughputs of 390 and 460 t/h.

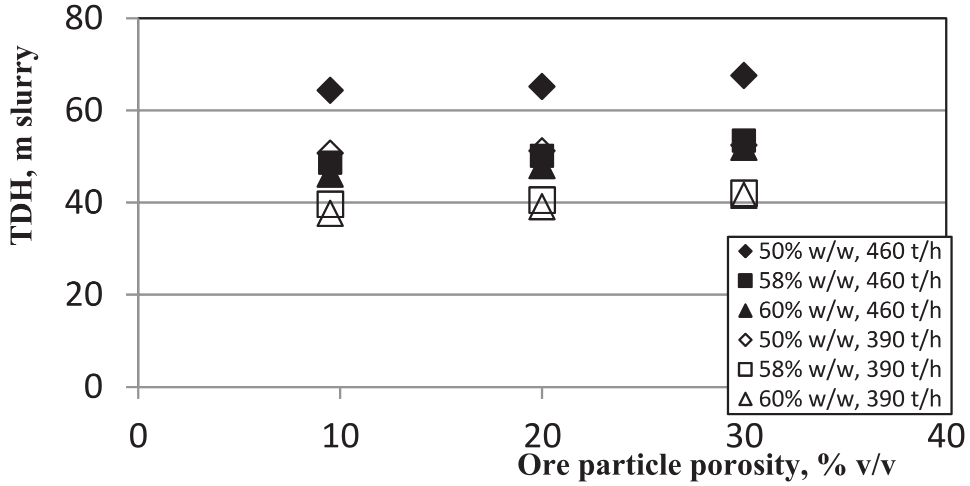

Fig. 6 Predicted TDH for the MP3 pipeline at 20^0C using the SRC 2007 PipeFlow model

As previously noted with the smaller diameter P5 pipeline, the predicted TDH is higher for the lowest ore concentrations of 50% and at the higher dry ore throughput of 460 t/h, but again the effect of the assumed ore particle porosity is small.

5. CONCLUSIONS

Based on frictional pressure losses across pipework and pipe fittings, predictions of the total dynamic head (TDH) across either two or three centrifugal slurry pumps in series in the P5 and MP3 phosphate ore distribution pipelines have demonstrated that the assumed values of the ore particle porosity over the range of 9.5% to 30% is relatively unimportant compared with the effects of ore concentration and dry ore solids throughputs.

The relative insensitivity of the predicted frictional pressure gradients for pipe flow, and the corresponding TDH estimates as the assumed ore particle porosity is varied within the range of 9.5% to 30% can be explained as follows. As the particle porosity is increased, so the effective particle density is reduced and it is assumed that all the pores are filled with water having a lower density than the skeletal density of the particle. The result is that a less dense particle will require less turbulent energy to support and transport it through a horizontal pipeline, and so a lower frictional pressure gradient would be expected.

However, increasing the assumed porosity of a particle will also have the effect of increasing the solids volume fraction in the slurry for a constant solids mass fraction and particle size distribution, and this will tend to increase the pipeline frictional pressure gradient. When the two effects are closely balanced, the result, as shown in this study, that the frictional pressure gradient is relatively insensitive to changes in particle porosity over the range assumed here.

Of course, over a wider range of particle porosities and over a different range of solids volume fractions in the slurry, this may not be the case. A further variable is also the particle size distribution which may also cause one effect to dominate over the other.

A future study could investigate the effects of wider ranges of particle porosity, solids volume fraction and particle size distribution on the estimated frictional pressure gradient using the SRC PipeFlow model and also other models predicting frictional pressure gradient.

These findings are based on friction pressure gradient predictions generated by the SRC 2007 PipeFlow software, without any measured pipeline friction pressure gradient data to confirm the reliability of the software predictions and are therefore subject to the possible assumptions and limitations of the SRC software.

However, the two pipelines described here together with eight other pipelines have now been installed and commissioned successfully.

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