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CENTRIFUGAL PUMP PERFORMANCE DERATING FOR COARSE PARTICLE AND HIGHLY CONCENTRATED SETTLING SLURRIES

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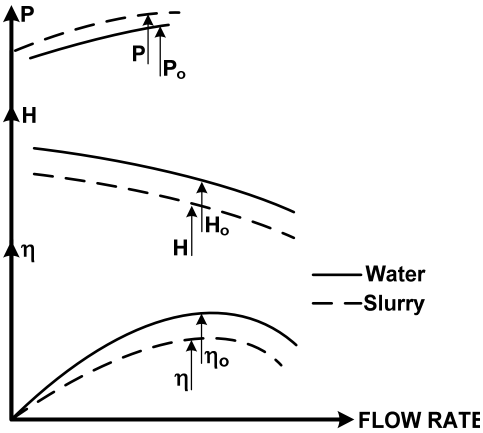
Abstract: The presence of particles in settling type slurry flow tends to produce adverse effects on centrifugal pump performance, reducing developed head and efficiency. The objective is to present and discuss settling slurry pump performance results with focus on the derating in efficiency. The current Hydraulic Institute centrifugal pump performance derating procedure for pump head when handling settling slurries, ANSI/HI(2011),was mainly confirmed with the data used here. The pump efficiency appears to be more sensitive to the solids properties and individual design factors than head effects and therefore, modeling of the pump efficiency losses is more complex. The relative deratings of head and efficiency are here represented by a factor, c, which is multiplied by the relative slurry density and the power requirement for pumping water to determine the slurry pumping power requirement. The considered deratings are for narrowly graded particle slurries with a negligible amount of particles smaller than 0.1mm. Resulting deratings are mainly the outcome from controlled test loop data bearing in mind that the reduction in efficiency may be somewhat larger in practice. It was found that the factor, c, attains a value of about 1.1 for a volumetric solids concentration of 35% sand with an average particle size of 0.35 mm in a 0.37 m impeller diameter pump. A c-value of about 1.05 corresponded to a C_v of 45% for a 0.6 mm average particle size in a 1.1 m impeller diameter pump. A value for, c, of about 1.4 may represent a sand with an average particle size of 1.8 mm at a concentration of about 37% in a 0.4 m impeller pump.

KEY WORDS: centrifugal slurry pump, settling slurry, performance derating,

1. INTRODUCTION

The energy consumption in a pumping system is related to the energy to overcome elevation change, friction losses and the efficiency of the used pumps. The energy effectiveness is thus the combined outcome of the slurry pipeline and pump performance. The presence of particles in the slurry flow tends to produce adverse effects on centrifugal slurry pump performance, reducing developed head and efficiency. The relative derating of the clear water head and efficiency for a constant flow rate and rotary speed may be defined by the ratios and factors shown in Figure 1.



Head ratio: $HR = H/H_0$

Efficiency ratio: $ER = \eta/\eta_0$

Head reduction factor: $R_H = 1 - HR$

Efficiency reduction factor: $R_\eta = 1 - ER$

H =head in slurry service

H_0=head in water service

η = pump efficiency in slurry service

η_0= pump efficiency in water service

Figure 1. Sketch defining the derating in head and efficiency of a centrifugal pump transporting a settling type of slurry. P is power requirement in slurry service and P_0 is power requirement in water service.

For a liquid with density greater than water, but with viscosity equal to water, the flow inside the pump is substantially unaffected. In this case, HR=1 and ER=1. The power consumption is then determined by the relative liquid density (or specific gravity) multiplied by the power requirement for pumping water. This corresponds to a particle-liquid mixture exhibiting pseudo-homogeneous or “equivalent fluid” behaviour, where the solids remain well mixed and suspended within the fluid. With other settling type slurries, performance reduction may occur and the power requirement can be represented by a factor, c, which is multiplied by the “equivalent fluid” power (i.e. the relative slurry density times the power for pumping water), to obtain the slurry pumping power requirement. The factor, c, is related to the different effects of the particle content on both head and efficiency.

In the literature, performance derating correlations for settling slurries are mainly focused on the effect on head. This is due to the importance of the pump head curve in determining the required pump operating speed and flow through interaction with the pipeline system resistance curve. Settling slurry system resistance curves are often relatively “flat” and display a slow rise with increasing flow rate. Therefore even small reductions in pump head caused by the solids effect can produce a disproportionately large drop in flow rate. Furthermore, the head effects are not influenced as much as the efficiency by the solids properties and individual pump design factors and therefore, modeling of the pump efficiency losses is more complex. Rather than attempting to calculate the efficiency solids effect, it is often assumed to be similar to the head effect and a margin of 15 to 25% is then placed on the installed driver power to account for any uncertainty. However, in settling slurries where the solids concentration is high, (above 20% by volume), or the solids are very coarse, the efficiency reduction may be considerably greater and a more precise calculation may be desired.

In the HI ANSI/HI Standard 12.1-12.6 (2011) for Rotodynamic (Centrifugal) Slurry Pumps covering slurry nomenclature, definitions, applications and operation; the effect of solids on pump performance is covered along with classification of settling slurry services which are used to determine limitations on total head per pump for best wear performance. A generalized diagram procedure for estimation of the solids effect on head for settling slurries is also given. See the Appendix of how to apply this method and the definitions in Figure 1, using a detailed example of a heavy ore product where the influence of the properties of solids, solids concentration and pump size are included.

Although separate from the solids effect, additional deratings of 10 to 15% should be anticipated for settling slurries due to wear of the pumping components over time. This is often accounted for in the design of the system, or by providing a variable speed drive with an additional 10 to 15% margin on the pump speed after adjustments for the solids effect on head have already been included.

2. OBJECTIVE AND SCOPE

The objective is to present and discuss settling slurry pump performance results with focus on the derating in efficiency. The considered deratings are for narrowly graded particle slurries with a negligible amount of particles smaller than 0.1mm. Resulting deratings are mainly the outcome from controlled test loop data, bearing in mind that the reduction in efficiency may be somewhat larger in practice, since the closed loop nature of lab testing often results in more solids degradation than is seen in the typical "once-through" industrial application. Head derating estimations for the experimental data have been compared with the Hydraulic Institute centrifugal pump performance derating procedure for settling slurries, ANSI/HI(2011).

3. CHARACTERIZATION

The power output of a pump is determined by the product of the slurry or water pressure ($\rho \cdot g \cdot H$ and $\rho_0 \cdot g \cdot H_0$ respectively) and the flow rate, Q, divided by the corresponding slurry or water efficiency:

$$P = \rho \cdot g \cdot H \cdot Q/\eta \qquad 1$$

$$P_0 = \rho_0 \cdot g \cdot H_0 \cdot Q/\eta_0 \qquad 2$$

where ρ and ρ_o are the density of slurry and water respectively and g the acceleration due to gravity. It follows that the ratio of the power requirements for slurry, P, and water, P_0, from Eqs. 1 and 2 can be expressed as follows, together with the definitions in Figure 1:

$$P/P_0 = S\frac{HR}{ER} = S\frac{1-R_H}{1-R_\eta} \qquad 3$$

where, S, is the relative slurry density.

$$S = \rho/\rho_o \qquad 4$$

When the reductions in head and efficiency are equal:

$$HR = ER \text{ or } R_H = R_\eta \qquad 5$$

then the power consumption when pumping slurry increases directly with the relative density of the slurry.

$$P = S \cdot P_0 \qquad 6$$

In situations when:

$$HR > ER \text{ or } R_H < R_\eta \qquad 7$$

then eq.3 corresponds to:

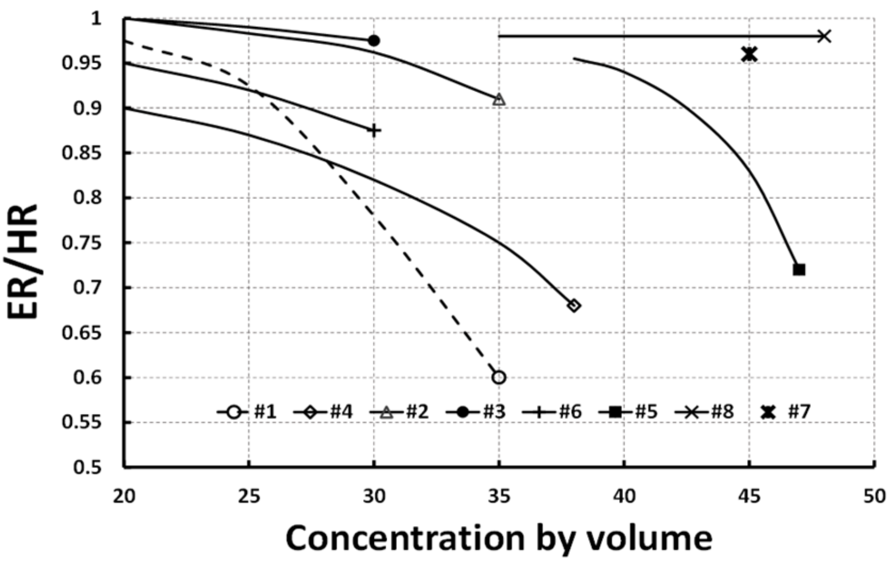
$$P > S \cdot P_0 \qquad 8$$

and the power consumption increases more than expressed by the relative slurry density times the water power requirement (i.e. greater than predicted by the equivalent fluid model).

3.1 HIGH SOLIDS CONCENTRATIONS

The current Hydraulic Institute centrifugal pump performance derating procedure for settling slurries (see Appendix), ANSI/HI(2011),was mainly confirmed for head effects with the data used here.

The successive development in slurry pump design from the early 1980s also means that head and efficiency deratings in general have become smaller without sharp reductions in efficiency for volumetric solids concentrations, C_v ,greater than about 20%. For example, Walker et al. (1992) showed in comparative tests how the vane shape had a pronounced positive effect for narrowly graded sands ($d_{50}=$ 0.4 and 0.8mm) in pumps with impeller diameters of 0.3-0.4 m. However, Walker et al. (1992) found a trend that the value of ER would still be less than HR for C_v greater than 20%. The results by Walker et al. (1992) are shown in Figure 2 together with some other published investigations from loop tests at the GIW Hydraulic Laboratory and other sources. These are expressed according to the ratio ER/HR, so values less than 1.0 indicate a solids effect on efficiency greater than the solids effect on head.



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Legend: Average particle size,d_{50} in mm.Pump impeller diameter,D, in m.

Test s	d_{50}/D	Comments
1	0.1/0.43	Industrial mineral, 3-vane rubber-lined pump, Sellgren and Väppling (1986)
2	0.35/0.37	4-vane all metal pump, Walker et al.(1992)
3	0.28/ 0.4	3-vane all metal pump, Sellgren and Addie (1993)
4	1.8/ 0.4	3-vane all metal pump, Ni et al. (1999)
5	0.35/0.63	3-vane all metal pump, Wilson et al.(2006)
6	0.58/0.63	3-vane all metal pump, thick material sections, Sellgren and Addie (1993)
7	0.6/1.1	4-vane all metal pump, Sellgren and Addie (1993)
8	0.36/ 2.6	4-vane all metal dredge pump, Vercruisse and Corvelyen (2002)

Figure 2. The parameter ER/HR versus solids concentration by volume. Experimental results mainly from reported loop test data listed in the legend.

It follows from Figure 2, test #2, that a d_{50} of 0.35 mm and an impeller diameter of about 0.37 m result in an ER/HR ratio of about 0.9 at C_v 35%. A ratio of about 0.95 holds for #7 at C_v 45% with 0.6 mm d_{50} particles and 1.1 m impeller diameter. For the largest pump with an impeller diameter of about 2.6 m (# 8), the ratio of pump head and efficiency derates approached 1.0 and were independent of C_v for two sands with d_{50} of 0.28 and 0.45 mm, corresponding to an average d_{50} of 0.36 mm. This field study will be discussed in more detail in a subsequent section.

The results #1 from tests in the late 1970s reported by Sellgren and Väppling (1986) for a rubber-lined pump with industrial mineral solids of S_s=2.4 and 0.35 mm d_{50} show a sharp drop in ER/HR from C_v about 25%. More moderate results of other tests may reflect the development in pump design since that time. Tests #5 and #6 are for modern pumps of similar size and design, however #6 required thicker material sections for wear allowance. The considerably greater derating effect starts at C_v already below 20% and may not be related to the larger particle size alone.

The coarse particle result #4 by Ni et al.(1999) with d_{50} =1.8 mm and strong derating with ER/HR <1 already before 20%, reaching 0.7 at a C_v of about 37%, shows how coarse particles in comparatively small pumps can lead to significant derating effects.

The detailed development of HR and ER for the test denoted #5 in Figure 2 with C_v increasing from about 35 to over 45% are shown in Figure 3.

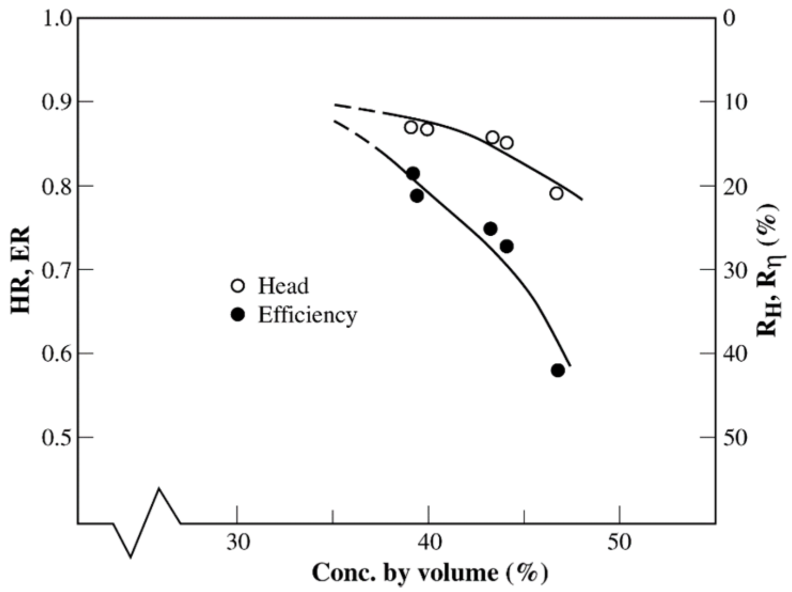

Figure 3. Reduction in head and efficiency at high solids concentrations for a sand with d_{50} = 0.35 mm and an all metal pump (impeller diameter = 0.63 m).From Wilson et al.2006.

The increasing power requirement corresponding to ER/HR<1 in Figures 2 and 3 can be represented by a factor, c >1, in eq.3 (Sellgren et al.2002).

$$P = c \cdot S \cdot P_0 \tag{9}$$

where the factor , c, is defined as follows:

$$c = \frac{HR}{ER} = \frac{1 - R_H}{1 - R_\eta} \tag{10}$$

The ER/HR values 0.95 and 0.9 discussed above correspond to, c, values of 1.05 and 1.1, respectively, while a value of about 1.4 corresponds to ER/HR approaching 0.7 in Figure 2. It should be noted that the solids related deratings discussed here in terms of, c, do not include margins for loss of pump efficiency due to the wear of the pumping parts, or the safety factor associated with the motor rating and losses in the drive train.

3.2 COARSE AND HEAVY PARTICLES

Evaluated derating results for narrowly graded coarse gravel and rock particles with average sizes from 9.5 mm up to 25 mm and a narrowly graded coarse iron ore with S_s=4.39 are given in Table 1 in terms of the measured ratios HR and ER for given impeller diameters, D.

Table 1: Evaluated pump deratings for narrowly graded coarse particles. Maximum particle size, d_{max} , and, d_{50} ,in mm

Gravel and rock S_s= 2.65

d_{50}	d_{max}	C_v	D	HR	ER
9.5	13	24	0.79	0.80	0.78
25	65	20	0.81	0.83	0.78

Iron ore product S_s= 4.39

d_{50}	d_{max}	C_v	D	HR	ER
22.5	40	6.5	1.38	0.89	0.82
22.5	40	8	0.91	0.83	0.81

The measured HR and ER values from Table 1 for the rock and coarse heavy ore product at average C_v of 22 and 7%, respectively, showed that ER were slightly less than HR corresponding to values of 0.93-0.97 for the parameter ER/HR in Figure 2. The corresponding maximum c–value (eqs. 9,10) was 1.08.

For the coarse iron ore product at 6.5 and 8% the ANSI-calculated values of HR were 0.95 and 0.91, respectively, with measured values of 0.89 and 0.83, i.e. the head reduction factors were about double the estimated values with the Hydraulic Institute procedure in the Appendix. This may partly be related to the fact that the particles were very angular.

4. DISCUSSION AND CONCLUSIONS

The current Hydraulic Institute centrifugal pump performance derating procedure for pump head when handling settling slurries, ANSI/HI(2011), was mainly confirmed with the data used here. While the standard addresses primarily head effects, it recommends in most cases that the ratio ER/HR be taken as approximately = 1.0, since the actual deviation from 1.0 can usually be accommodated by typical safety factors applied on rated driver power. Particular cases where ER/HR approximates 1.0 include most applications where C_v < 15%, as well as with larger pumps, as shown by the following:

- The derating results for a 2.6 m impeller pump (Vercruijsse & Corveleyn 2002) in Figure 2 indicated that ER/HR approached 1.0. However, a detailed evaluation showed a trend of ER/HR to be close to or slightly greater than 1. This corresponds to $P < S \cdot P_0$ in eq. 6. ER/HR increased monotonically from approximately 1 to 1.05 for C_v from 20% to 50%, respectively, for a sand with d_{50} 0.76mm. The corresponding ER/HR increase for a 1 mm d_{50} sand was from 1.0 to about 1.1.

- A similar trend of increasing ER/HR from 1.0 to 1.06 for narrowly graded sands and gravel in the 0.25 to 6 mm d_{50} particle size range, respectively, where reported by Sellgren and Addie (1989) in loop tests at C_v=15% in pumps with a impeller diameters of 1.1 and 1.2 m. ER/HR>1 has also been observed for sand or ore based slurries with fine particles < 75 µm containing clay Sellgren (2000) or for an ore containing some talc which is a friable waxy mineral with a pronounced lubrication effect, Sellgren (1979). With the settling slurries without a fine particle content discussed above, c, exceeds 0.9 and in industrial practice it is reasonable to design for c=1, i.e. $P=S \cdot P_0$.

The Hydraulic Institute standard does, however, acknowledge that ratios of ER/HR significantly < 1.0 (i.e. c significantly > 1.0) are possible for highly concentrated slurries of C_v > 20%. In particular:

- It is concluded from the evaluations in Figure 2 that the factor, c, attains a value of about 1.1 for a volumetric solids concentration of 35% for a sand with an average particle size of 0.35 mm in a 0.37 m impeller diameter pump. A slightly smaller c-value of 1.05 was found at C_v 45% for a 0.6 mm average particle size with a 1.1 m impeller diameter pump. The reported tendency for even larger pumps with C_v approaching 50% is that HR≈ER≈1, i.e., a c-value of about 1.0.
- A value for, c ,of about 1.4 may represent a coarse sand with d_{50} =1.8 mm at a concentration of about 37% in a 0.4 m impeller pump
- A c-value of about 1.1 were found for rock (d_{50} =9.5 and 20 mm) and heavy ore (d_{50}=25 mm, S_s=4.39) at average concentrations of 22 and 7%, respectively, in pumps with impeller diameters of about 0.8m.
- Individual product properties and pump design factors like thick material sections in the pump impeller may further increase the c value.

In general, ER appears to be more sensitive than HR to the slurry and pump design parameters influencing solids effect derates and is therefore more difficult to predict with accuracy. However, a trend towards c values greater than 1.0 in highly concentrated slurries and smaller pumps indicates that application guidelines to account for this trend should be considered.

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APPENDIX

A generalized diagram for estimation of the performance derating in head for settling slurries according to ANSI/HI (2011) is given in Figure A1, see also Wilson et al. (2006).

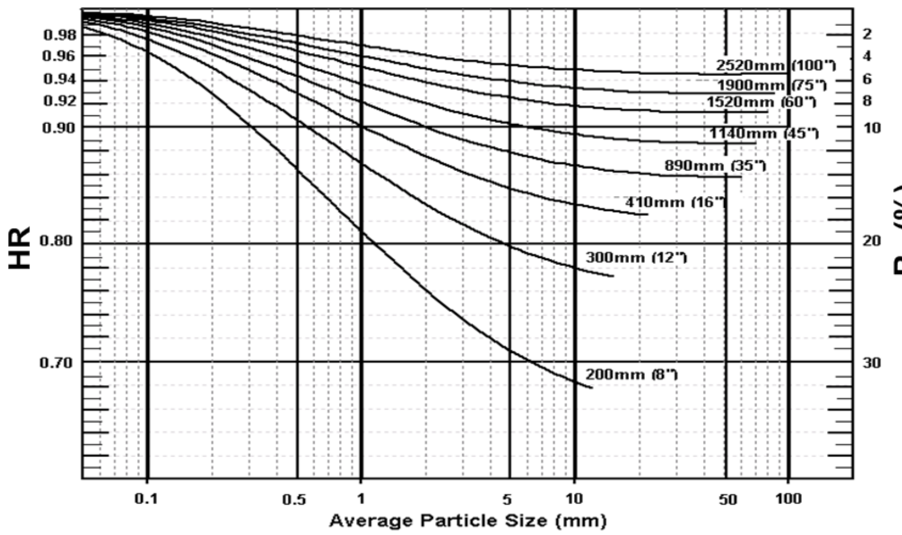

Figure A1.Generalised solids-effect diagram for pumps of various sizes (impeller diameters).For solids concentration by volume 15% with relative density of solids, 2.65, and a negligible amount of fine particles smaller than 75micron. From ANSI/HI (2011).

Arbitrary HR or R_H values from Figure A1 are then obtained through concurrent corrections for solids concentration, relative density and content of particles smaller than 75 micron, X_h:

Concentration by volume	Solids relative density	Fine particle content
$C_v/0.15$	$\left[\frac{S_s-1}{1.65}\right]^{0.65}$	$(1- X_h)^2$
0.295/0.15= 1.97	$(4/1.65)^{0.65}$=1.78	1

<u>Example</u>: Pumping of 100 m^3/h of a heavy ore product at C_v=29.5% and head of 19.5 m slurry. The product has a solids density of 5000 kg/m^3 with no particles finer than 0.1mm, d_{50}= 0.55 mm and d_{max}=1 mm. Pump impeller diameter=0.3 m.

With d_{50}=0.55 and D=0.3m, the diagram in Figure A1 gives HR and R_H of 0.90 and 10%, respectively. The concurrent corrections above give R_H=10 ·1.97·1.78=35% or HR=0.65. The head and efficiency ratios were defined in Figure 1.

To produce the required slurry head of 19.5 m, the pump must be capable of producing a water head, H_o=H/HR= 19.5/0.65 =30 m. Assuming a pump head-capacity characteristic as seen in Figure A2, the rotary speed must be increased from 1240 to 1500 rpm.

For this example, it is assumed that the water efficiency, η_o , at 1500 rpm and 100 m^3/h is 68%. It is also assumed here that ER is low, at only 0.4, which is considerably less than HR=0.65. The water efficiency is then reduced to the slurry efficiency, $\eta = 0.68 \cdot 0.4 = 0.272$, which is used in the calculation of the power requirement for the duty of 19.5 m slurry head, 100 m^3/h (0.0278 m^3/s) of slurry flow, slurry efficiency of 27.2% and slurry density, which can be calculated to 2180 kg/m^3 based on the given solids density and concentration by volume.

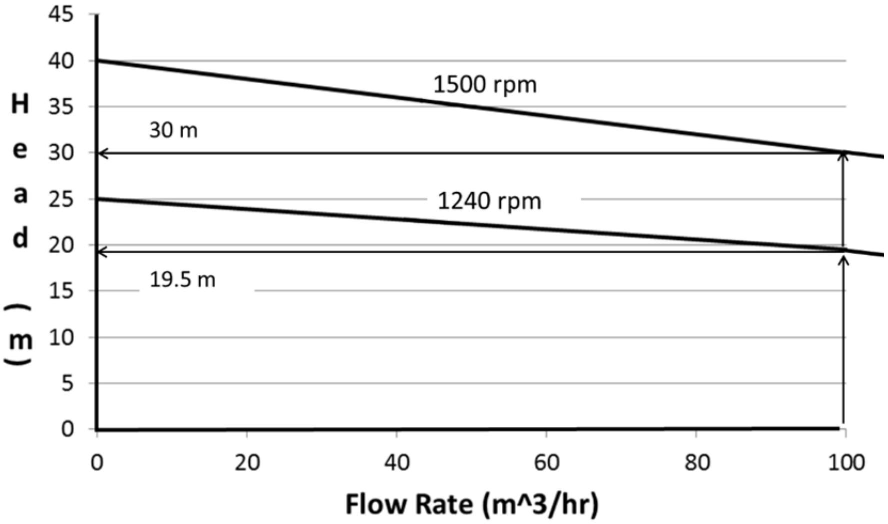

Figure A2. Pump head curves for 1240 and 1500 rpm approximated as straight lines for the considered flow rates and heads. To maintain the operating point at 19.5m for 100 m^3/h the pump has to develop 1500 rpm to account for the derating effect.

These values are then used to calculate the power requirement:

$$P = \frac{\rho g H Q}{\eta} = \frac{(2180)(9.81)(19.5)(0.0278)}{0.272} = 42620W = 42.6\,kW$$

The derating ratios in head, HR, and efficiency, ER, were here 0.65 and 0.4, respectively, requiring an increase in rotary speed from 1240 to 1500 rpm and giving a pump efficiency of about 27%. The example is a slight modification for demonstration purposes of loop test results with an iron ore product.