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ABSTRACT: In several industries, like the mining business, it is very common to observe high head pumping systems, which transport water to more than one discharge point. These discharge points could have, in some cases, variable discharge pressures and, furthermore, could be utilized as water sources (a water reservoir, for example) for other facilities using the same pipes that feed them (flow in double direction). Because of this particular design, the pumping systems can have different Total Dynamic Head (TDH) depending on the water level in the reservoir(s), resulting in a complication for the design and operation of the pumping systems. The objective of this investigation is to understand the operation of pumping systems with variable reference head, visualize the advantages of this type of design, and better understand related operating problems. In this case study, we analysed the design of an existing system that transports water from a river to a 4.2 million m^3 reservoir and then on to a base metal process plant. To address this problem, a steady-state analysis was conducted to determine the TDH and flow discharge per pump for several operation scenarios and different types of problems noted from the calculations performed. The first problem was related to the control system being required to supply pumped water directly to the process plant and to the reservoir at the same time. Another problem was related to the performance of the pumps in all pump stations: a broad range of operation in terms of flow discharge. To avoid this type of problem, a redesign or mitigation measures should be considered, like the use of variable frequency drives for the pump motors or the increase of the water tank volume in pump stations. A redesign of the system was proposed as a result of this investigation.

Keywords: pumping systems, total dynamic head, water pipelines, steady state analysis.

INTRODUCTION

In some mining and industrial projects, rivers are the main water sources near to the process facilities. To take advantage of this resource, the water is pumped from the river to an elevated reservoir (LOCHER et al. 2000). In some cases, industrial projects prefer to use part of the same pipe that supplies river water to the reservoirs as an outlet pipe (bi-directional pipe flow) to convey water from the reservoir to other process plant facilities under gravity flow, for economical purposes.

However, this design can lead to a more complex problem because pumping systems have different Total Dynamic Head (TDH) depending on the water level in the reservoir(s). The water level fluctuations in this specific reservoir can be 30 meters, creating a broad TDH operation range for the pumps. Or, in other cases, the difference of elevation between the river and reservoir can exceed 600 meters with high flow rates (~ 4 000 m^3/h), which requires the use of more than one pump station in series, adding additional operational complexities.

These kinds of problems, in general, are not considered in the early stages of engineering since they are operational issues and, at the preliminary phases, it’s believed that when fewer elements are considered in the initial design, the possibility of reducing investment costs increase. However, a simple redesign may prevent future difficulties in pump systems for these cases.

This study analysed an actual design, which consists of a pumping system to transport water from a river to a 4.2 million m^3 reservoir and a 0.91-m (36-inch) diameter branch pipe to convey water to a base metal process plant. The pumping system must be capable of transporting water from the river to the reservoir and, at the same time, supplying water to the process plant. The system considers three pumping stations in series with a maximum flow rate of 4,200 m^3/h. A single 0.91-m pipe connects each pump station. Each pump station operates with four pumps in parallel and considers the use of a water tank. A schematic of the water supply system is presented in Figure 1.

METHODOLOGY

To analyse the system previously described, the energy balance and continuity equations applied to fluids were used. These equations are represented as follows [Eqs. (1) and (2)] (MUNSON et al, 2002),

$$z_1 + \frac{P_1}{\gamma} + \frac{V_1^2}{2g} + TDH = z_2 + \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + \Lambda_{1-2} \qquad (1)$$

$$\Lambda_{1-2} = f\frac{L_{1-2}}{D}\frac{V^2}{2g} \qquad (2)$$

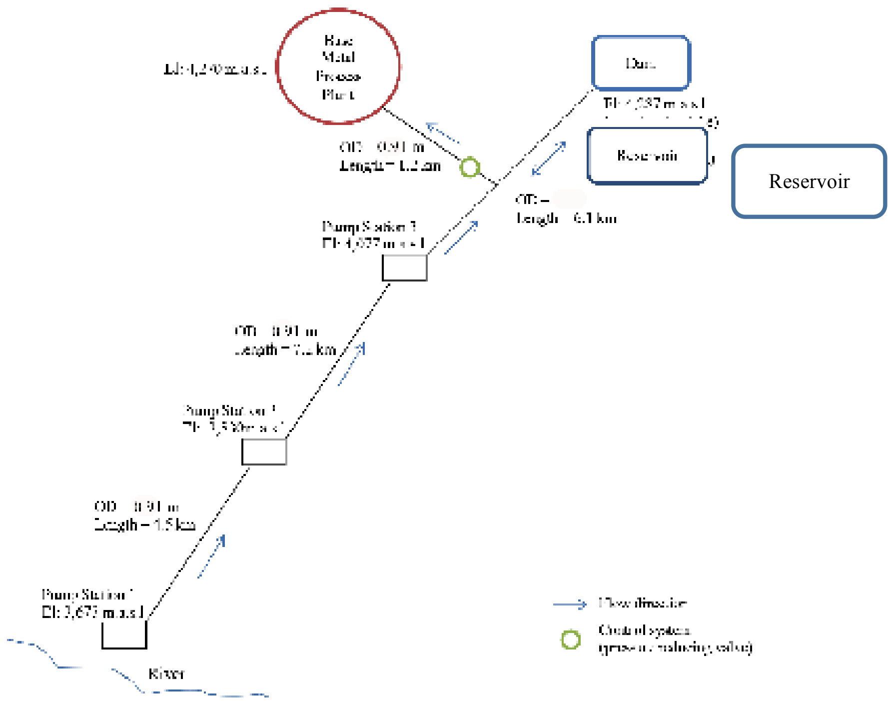

Figure 1 – Schematic representation of pumping system. All the pump stations operate with four pumps in parallel. The first pump station uses vertical pumps and the rest of the pump stations use centrifugal pumps with horizontal axis.

Eq. (1) represents the Bernoulli's equation and Eq. (2) is the Darcy-Weisbach equation for a pressurized water pipeline. In this equation, subscript 1 represent the pump station (initial point in the pipeline) and subscript 2 represent the end point at the pipeline discharge. Subscript 1–2 in Eq. 2 is used to represent the frictional head loss between points 1 and 2 of the pipeline. For a conceptual design, the minor head losses could be assumed as a percentage of the frictional losses. In this case, 5% was assumed. The continuity equation was applied for a pressurized system at the divergent point where the flow from Pumping Station N°3 must be equal to the sum of the divergent flow rates.

The friction factor of the Eq. (2) is obtained from the Colebrook-White equation [Eq. (3)] (MUNSON et al, 2002),

$$\frac{1}{\sqrt{f}} = 1.14 - 2 \cdot \log\left(\frac{k_s}{D} + \frac{9.35}{Re \cdot \sqrt{f}}\right) \tag{3}$$

where, Re represents the Reynolds number, which is computed as follows:

$$Re = \frac{V_1 \cdot D_{1-2}}{\upsilon} \tag{4}$$

By means of the pumps catalogue provided by ITT GOULDS PUMPS (2004) it was possible to obtain the pump curves necessary to convey the flow required for the TDH computed. These pump curves should be compared with Eq. (1) to obtain the operation point of the pumps with the final TDH and flow for one, two, three, and four operating pumps. The results obtained are shown in the next section.

RESULTS AND DISCUSSION

The principal results obtained from the steady-state analysis are the Hydraulic Grade Line (HGL) profiles for the main pipeline, which connect the three pump stations and the operation curve of the entire system. The pipeline HGL from Pump Station N° 3 to the Reservoir (see Figure 1), is presented in Figure 2. These data presented in Table 1 show the difference between the TDH for the full reservoir case and the empty reservoir case. Table 1 also shows the TDH for the Pumping Station N°1, N°2 and N°3.

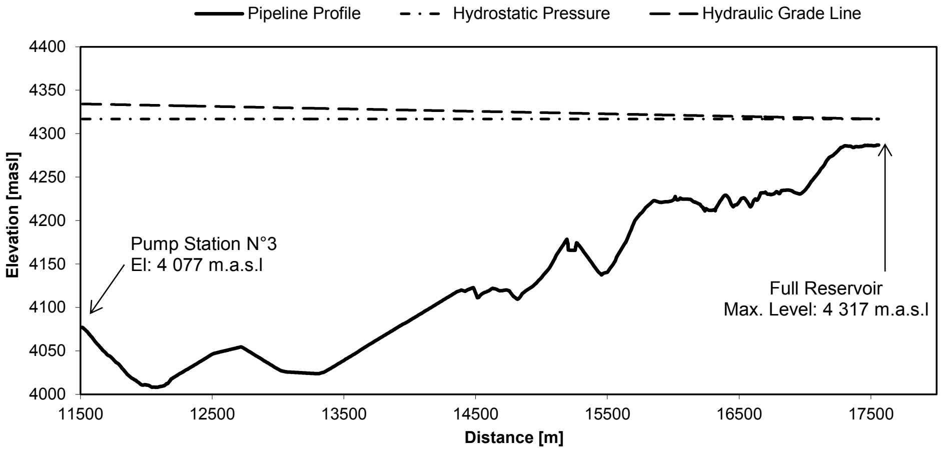

Figure 2 – Hydraulic Grade Line for water pipeline system starting at Pump Station N°3 to the Reservoir. Full-reservoir case.

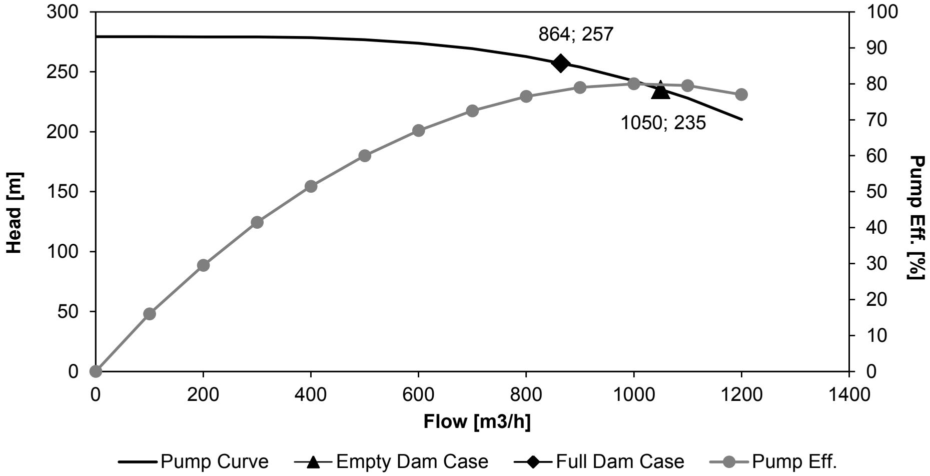

Figure 3 – Operation Points for each pump of the Pumping Station N°3.

Table 1 – Results obtained from steady-state analysis for all pump stations.

Pumping Station	N° of Pumps	Flow per pump [m^3/h]	Total Flow [m^3/h]	Total Dynamic Head [m]
1	1	1 239	1 239	177
	2	1 195	2 390	181
	3	1 126	3 377	187
	4	1 047	4 188	194
2	1	1618	1 618	268
	2	1444	2 889	277
	3	1239	3 716	287
	4	1051	4 203	293
3 (*)	1	1192	1 192	212
	2	1159	2 318	218
	3	1112	3 336	226
	4	1050	4 199	235
3 (**)	1	1008	1 008	241
	2	975	1 950	245
	3	926	2 778	251
	4	864	3 457	257

(*) Results obtained for the minimum water level in the reservoir (empty reservoir case).
(**) Results obtained for the maximum water level in the reservoir (full reservoir case).

From the results shown in Table 1, a significant difference between the flow per pump for the empty reservoir case and the full reservoir case can be observed. A 185 m^3/h average difference between the two cases (which represents 21% of the per-pump discharge by each pump in the full reservoir case) shows the broad operational range required for the pumps in the third pumping station (see Figure 3). Another observation from the results obtained is the performance of the entire pumping system. In the full reservoir case, the maximum pumped flow will be 3,457 m^3/h if all pumps are working at pump station N°3. For this case, if all pumps are also working in pump stations N°1 and N°2, a non-balanced system will result and Pump Stations N°1 and N°2 will need to shut-down to avoid overflowing in the water tank at Pump Station N°3. Obviously, this will decrease the flow delivered to the processing plant installations. Besides, if the water level diminishes to lower values than Net Positive Suction Head (NPSH) required for the proper functioning of pumps (KARASSIK et al. 2008; WERTH and FRIZZELL 2009; ANSI/HI 1998) in the water tanks at Pump Stations N°1 and N°2, this will carry problems of cavitation that may damage parts of the pumps.

CONCLUSIONS AND FINAL REMARKS

In the present work a complex pumping system has been analysed with a variable reference head. This work showed some problems commonly non-visualized that could lead to operational failures if not taken into account. The non-visualized problems and some solutions for them are:

1. Different Total Dynamic Head, which leads to two different operation points on the pumps' operation curve, with a difference of 21% in the flow pumped.
2. Because of the difference between the flow pumped for the full reservoir case and empty reservoir case, it is necessary to switch-off one pump at Pump Station N°1 and Pump Station N°2. A solution may be to utilize a water level monitoring system in pump station water tanks that turn off pumps when the tank is full and to avoid problems of cavitation problems when the water level is lower than NPSH required.
3. If a non-balanced system is established, an increase of water tanks volume would be necessary to avoid exceeding the overflow level and to keep delivering water required by the base metal process plant.
4. From the above conclusion, a variable frequency driver would be necessary in order to equilibrate the flows between the three pumping stations (KARASSIK et al. 2008).

A redesign could be considered to avoid these problems. A first design recommendation would be to consider an atmospheric discharge to the reservoir from Pump Station N°3. This would avoid the dual operation point in the pump curve and the difference of 21% of pumped flow between the extreme cases analyzed. Furthermore, this would permit a better performance of the three pump stations and help to avoid a non-balanced system with additional elements, such as bigger water tanks or variable frequency drivers for the pumps. Give this redesign, a second pipe to convey water from the reservoir to the Plant Facilities should be considered, and a hydraulic transient analysis should be carried out to design the final pipe dimensions and hydraulic transient mitigations. Finally, these solutions may increase the project investment costs, so all the alternatives should be economically analyzed.

LIST OF SYMBOLS

z_1	=	geometry elevation at the upstream node pipe (m).
z_2	=	geometry elevation at the downstream node pipe (m).
P_1	=	pressure at the upstream node pipe (Pa).
P_2	=	pressure at the downstream node pipe (Pa).
V_1	=	flow velocity at the upstream node pipe (m/s).
V_2	=	flow velocity at the downstream node pipe (m/s).
γ	=	specific gravity of the fluid (N/m3).
G	=	gravity acceleration (m/s2).
F	=	pipe friction factor (non-dimensional).
$L_{1\text{-}2}$	=	pipe length between the nodes upstream and downstream (m).
$D_{1\text{-}2}$	=	pipe diameter between the nodes upstream and downstream (m).
$\Lambda_{1\text{-}2}$	=	frictional energy loss (m).
k_s	=	pipe wall equivalent sand grain roughness (m).
υ	=	fluid kinematic viscosity (m2/s).
TDH	=	total dynamic head of the pump (m).

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