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A cost perspective for long distance ore pipeline water and energy utilization. Part I: Optimal base values

Christian F. Ihle *

Advanced Mining Technology Center, Universidad de Chile, Blanco Encalada 2002, Santiago, Chile
Department of Civil Engineering, Universidad de Chile, Blanco Encalada 2002, Santiago, Chile

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ABSTRACT

Long distance ore pipelines are intensive in water and energy use. Although past efforts have been made to identify the best operational points in terms of energy efficiency, an approach to concurrently include water value, representing aspects such as price or scarcity, is lacking. In the present paper, an optimization scheme to look for better operational points considering energy and water utilization is proposed. A scalar function built upon the computation of energy and water consumption including restrictions inherent to hydraulic transport of solids through pipelines is defined. The relative importance of energy and water consumption is parameterized through the inclusion of water and energy unit costs, along with system variables such as throughput, solids concentration and system utilization fraction. The optimization problem is solved for different throughput and hydraulic conditions resembling a long distance copper concentrate pipeline and a range of water and energy costs, using a nonlinear, constrained optimization scheme. Results show the appearance of a low water cost regime for low throughput conditions, with a steep, quasi-linear change on optimal properties with water cost, followed by a nonlinear, high water cost regime, related to a weaker, monotonic change of concentration, flow rate, pipeline utilization and water consumption, respectively. For fixed water costs, increasing the energy cost causes an incentive for an additional use of water, thus appearing a double non-linear dependence of optimal results with energy and water costs.

For high enough throughputs, the low water cost regime disappears, and is replaced by constant, minimal optimal flow rate and solids concentrations, related to the maximum possible pipeline utilization constraint. Present results show that an equivalent pipeline oversizing at constant throughput would allow, in addition to the computed optimal conditions, for operation at lower specific energy consumption scenarios. Results, compared with some typical copper concentrate pipeline operational conditions, show that optimal values in the sense of the present hydraulic-cost analysis tend to require higher concentrations and lower pipeline utilization fractions than in typical systems, with differences in costs ranging from 16% to 28%.

1. Introduction

The hydraulic transportation of solids in turbulent flow using pipelines often requires large amounts of water to keep the solids suspended. Typical designs have more than 70% of the total transported volume in process or fresh water (Ricks, 2002; Betinol and Jaime, 2004; Chapman et al., 2009). On the other hand, provided that in many of those facilities, including several copper and iron concentrate pipelines connecting locations often distant more than 100 km apart (Abulnaga, 2002), the energy consumption is considerable, despite its efficiency compared to other transport technologies (Jacobs, 1991; Ekambara et al., 2009; Ihle, in press). This adds to the global reality of constantly increasing energy prices and, in some places including some desert areas in northern Chile, significant water scarcity problems that have raised questions on the feasibility of some new projects (Gaete, 2009; Bloomberg, 2012; Pizarro, 2012; Esposito and Cambero, 2012). Although this longstanding situation should drive alternative pipeline design approaches, it is somewhat paradoxical that transport design schemes virtually mimic those built almost 40 years ago (see Jacobs, 1991; Ricks, 2002; Betinol and Jaime, 2004, for a list of historical operational data). A possible explanation to this rather slow evolution is the lack of detailed knowledge of the slurry behavior after some startup/shutdown operations, such as solids sedimentation and consolidation in systems built upon complex topographies (Shook et al., 1974; Shook and McLeod, 1975; Ihle et al., 2011), thus encouraging rather conservative approaches both from the geometric and the slurry composition requirement standpoints. An outstanding exception to this observed tendency is the operational policy of the Samarco pipeline (Brazil) where concentration by volume has been progressively raised from about 28% in 1991 to almost 33% in 2009 (Santos et al., 2009). This initiative is a clear and illuminating argument to re-assess many existing long distance transport systems to seek for better operational

* Now at Mining Engineering Department, Universidad de Chile, Av. Tupper 2069, Santiago, Chile Tel.: +56 2 29784400.
E-mail address: cihle@ing.uchile.cl.

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states from the point of view of energy efficiency, lesser water consumption, or a conveniently defined combination of both.

Several studies have been made in the past to assess energy efficient operational points, considering the flow regime, particle size and concentration (Nguyen, 1998; Wilson, 2002; Wu et al., 2010; Ihle and Tamburrino, 2012c), but the relative importance of water and energy in light of the overall combined use of both in long distance ore pipelines, despite its relevance, has not been extensively studied. When considering solely energy as a decision driver, optimal solutions might be biased towards an intensive use of water and, therefore, a relatively high water footprint (Ihle and Tamburrino, 2012c). On the other hand, if the only important variable to be minimized is water consumption, optimal values would correspond to concentrations close to the loose packing value, where the corresponding energy use would be prohibitively high. It is therefore understood that both water and energy need to be used to fulfill production goals but, at the same time, preserved as much as possible according to some assessment of the economic, environmental and social implications of their use.

In this paper, a hybrid approach, both taking into account the effect of energy and water through their costs as weighting functions, is included as a scalar function. A set of optimal values for some critical operational parameters such as concentration and flow rate, given a throughput goal, has been obtained and shown quantitatively with an example close to some real long distance copper concentrate lines. It is shown here that such optimal conditions are strong and non-trivial functions of the corresponding unit costs. The paper is organized as follows: Section 2 contains a succinct overview of the hydraulic hypotheses adopted. Section 3 describes the optimization problem, including the formulation of the objective function. In Section 4, the details of the numerical approach and the results of the optimization problem for the example considered are analyzed. In Section 5, some results are compared with the particular case of typical operational conditions. Section 7 contains additional remarks that complement the present results and delineate possible future research work.

2. Hydraulic considerations

Consider the case of a pipeline of prescribed length L, an internal diameter D, with a given throughput goal, $\dot{m}$, transporting slurries with a narrow distribution of solids, following the Rosin–Rammler distribution:

$$\%\ \text{passing} = 100 \times \left\{1 - exp\left[-\left(\frac{x}{d_{\mathrm{RR}}}\right)^m\right]\right\}, \quad (1)$$

where m and d_{PR} are parameters representing the width of the distribution and particle size for which the 63.2% is smaller, respectively (du Plessis and Kearsley, 2007). The slurry is assumed to be well represented by the Binghammodel, defined as (Bird et al., 1983; Nguyen and Boger, 1992; Chhabra and Richardson, 2008):

$$\eta\frac{\partial u}{\partial z} = \begin{cases} 0 & \text{if } |\tau| < \tau_y \\ \tau - \tau_y sgn\left(\frac{\partial u}{\partial z}\right) & \text{if } |\tau| \geq \tau_y, \end{cases} \quad (2)$$

where u, η, τ and τ_y are the horizontal component of velocity along the pipe axis, Bingham (dynamic) plastic viscosity, shear and yield stress, respectively. The function sgn is defined as $sgn(x) = x/|x|$ if $x \neq 0$ and 0 otherwise. The pertinence of this rheological model in the context of ore concentrate flows has been discussed elsewhere (Ihle and Tamburrino, 2012b). It is assumed that particles are several dozens of microns in diameter and that wall shear rates are those corresponding to turbulent flows, with the implication that slurries are noncolloidal (see Ihle and Tamburrino, 2012c, for a scaling analysis). This is the case of many South American copper and iron concentrates, delivered from flotation plants to ports located hundreds of kilometers away, to which the study is focused (Ricks, 2002; Betinol and Jaime, 2004; Derammelaere and Shou, 2002; Chapman et al., 2009).

The procedure to compute the minimum transport velocity, U_{min}, which concurrently prevents solids deposition and pumping in laminar flow regime, is a variation of that described in Ihle and Tamburrino (2012c) and is described in refs: Appendix A. The friction losses are computed herein using the widely used model proposed by Thomas and Wilson (1987), with an additional penalty expressed as a roughness term, as detailed in Appendix B. To model the plastic viscosity with the slurry volume concentration the Maron-Pierce model (Maron and Pierce, 1956) is assumed:

$$\frac{\eta}{\mu} = \left(1 - \frac{\phi}{\phi_m}\right)^{-2}, \quad (3)$$

where ϕ and ϕ_m are the slurry solids volume fraction and the loose packing solids volume fraction, respectively. A comparison with copper and iron concentrate measurements, given in Appendix C, shows that (3) gives more than reasonable estimations at low to moderate concentrations, even considering the inherent distortions resulting from the buoyancy of solids and especially manipulation procedures (Ihle et al., 2013).

3. Cost function and optimization problem

3.1. Cost function

For a given pipeline geometry, the energy and water consumption in turbulent slurry pipeline transport is highly sensitive to slurry characteristics, where the concentration is the most important factor. For volume fractions exceeding about 0.3, small variations cause a relatively high impact on the mixture viscosity and pressure losses. This inevitable behavior makes preferable to consider direct measurements of rheology by means of online rheometers rather than only densitometers and flow meters (Shi and Napier-Munn, 1996; Akroyd and Nguyen, 2003; Ihle and Tamburrino, 2012b). However, from the water consumption standpoint, this high concentration condition is intuitively desirable as is bonded to a smaller water footprint. However, as the resulting embodied energy is a nonlinear function of concentration as well, too high solid fractions may result in energetically undesirable operating conditions. From the specific energy consumption viewpoint, it has been recently shown that non-trivial optimal values depending on the pipeline geometry, slurry characteristics, target throughput and pipeline utilization ratios sometimes suggest larger-than-usual operational concentrations (Ihle and Tamburrino, 2012c). A central point in the analysis proposed by Ihle and Tamburrino (2012c) is that the object of the optimization is the required energy to deliver a unit mass of *dry* matter over a unit pipeline length, given its diameter. Different from that case, the problem to be tackled here deals with a metric of an optimal combined use of water and energy, *via* a cost function. By solely considering the former element, the optimal transport scenario will be no water and virtually infinite energy to pump dry matter. On the other extreme, when water consumption does not matter at all and it is only the energy that which counts, then the resulting optimal scenarios are those as described by Ihle and Tamburrino (2012c).

The relative importance of water and energy use may be expressed as the linear combination of energy and water use, weighted by cost factors:

$$\Omega = c_E E + c_W \forall, \quad (4)$$

where Ω, the objective (cost) function, is expressed in cost units, $\forall$ is the volume of water spent in the pipeline in a certain period of time, and E is the amount of energy required to transport the slurry — not only the dry material — over the same period. c_E and c_W are the unit