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Computational modeling for efficient long distance ore transport using pipelines

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ABSTRACT

The term efficiency in hydraulic transport system design and operation has several possible interpretations. Whether it may stand for energy consumption, it may also aim to the minimization of the water or the carbon footprint. All these tentative means of efficiency should meet project and operational goals, including throughput constraints. The consideration of these aspects altogether, seeking for best project and operational conditions, represents a major optimization problem which, on the other hand, depends on the evolution of input variables for slurry transport along with environmental, energy and water consumption costs. In this paper, an example of a long distance ore pipeline with plant demand-dependent inputs is studied in the light of the implementation of an optimization problem. Results have been compared with those corresponding to typical transport modes, and show that common operational conditions differ from those optimized in terms of system utilization, flow rate and slurry concentration. In particular, the optimal computed parameters include lower fractions of the total available times, lower flow rates and higher concentrations than in typical systems, thus suggesting a different design and operational rationale.

1. Introduction

Long distance slurry pipelines are a widespread means of transport for iron and copper concentrates in South American locations including, Argentina, Chile, Brazil and Perú (Jacobs, 1991; Ihle, 2013a). They are traditionally designed according to specific hydraulic and site considerations inherited from the earliest designs, during the late sixties. Although such design rationale has been proven robust throughout the years, they do not directly deal with the increasingly challenging environmental scenarios, faced both in greenfield and brownfield projects. In particular, provided a set of representative economic and environmental indicators can be put together as cost indexes, even modern system designs lack of any consideration to this kind of element as an operational decision driver (Ihle, in press). Although long distance slurry pipelines are commonly commissioned and proven to work within a given operational range (Fig. 1), which allow for several different combination of throughputs (delivered dry solids), slurry concentrations and flow rates, there is not a special regard to which slurry concentration is best in terms of energy efficiency in combination with environmental metrics. Moreover, typical system operational ranges disregard the use of a variable system utilization fraction, defined as the part of the total time where the system will be effectively working. The simple exercise of drawing a horizontal line at a given throughput value, $\dot{m}$ (i.e. parallel to the flow rate axis in Fig. 1a), reveals not a single, but a collection of different solids volume fractions, ϕ, and slurry flow rate (Q) combinations (Fig. 1b). Which one to choose is a question often left to the operators or their supervisors who, in the absence of additional information to decide, tend to stick to familiar concentrations and flow rates, defined after the system startup phase. A possible operational choice is the highest possible concentration within the operational range, thus minimizing the water volume and consequently the water footprint of the operation. However, this causes an increase on the energy consumption that may somewhat create a worse operational condition (Ihle and Tamburrino, 2012b). A natural question is then to elucidate, not only which are the best flow rate-concentration combinations given the slurry properties and the throughput characteristics, but also which are the best system utilization fractions (λ). In this paper, this problem is analyzed in the context of an optimization problem where the relative effect of energy and water use are included as weighting factors in the form of unit costs. Emphasis is placed herein in the effect of a variable system throughput demand, thus complementing a previous analysis centered on the effect of variable unit costs (Ihle, 2013a),

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Nomenclature

Ar	Archimedes number
c	unit cost
D	pipeline internal diameter
E	energy consumption (Eq. (7))
f	Darcy friction factor
Fr	Froude number
g	magnitude of gravity acceleration vector
k	design constant for minimum velocity
L	pipeline length
$\dot{m}$	dry solids flow (throughput)
p	pressure
Q	flow rate
Re	Reynolds number
S	specific gravity of solids
T	time per period
U	mean flow velocity
W	water consumption (volume/period, Eq. (9))
x	route position along tube length
z	route altitude measured from an arbitrary datum

Greek letters

α	prefactor
β	exponent
ϵ	efficiency of pumping system
λ	pipeline utilization fraction
μ	liquid dynamic viscosity
η	Bingham plastic viscosity
ϕ	solids volume fraction
ρ	slurry density, $\rho = \rho_W(S\phi + 1 - \phi)$
τ	shear stress
$\hat{\tau}$	yield stress prefactor
Ω	cost function (Eq. (9))

Subscripts

0	general definition
50	median size
$*$	optimal value
c	critical condition
d	solids deposition condition
E	related to energy
f	related to the friction factor
J	related to the hydraulic gradient
max	maximum condition
min	minimum condition
SS	loose packing (settled solids) condition
t	laminar–turbulent transition condition
v	vapor pressure condition
W	related to water (e.g. ρ_W is the slurry density)
w	related to wall
y	yield (applied to the concept of yield stress)

additionally adding a terrain constraint in the example being analyzed.

2. Problem formulation

Consider an operating long distance slurry transport system with known internal diameter (D) where the throughput ($\dot{m}$), defined as the dry solids rate, along with route and slurry properties are known. The total energy and water cost may be expressed as:

$$\Omega = c_E E + c_W W, \quad (1)$$

where c_E and c_W represent the unit costs of energy and water, respectively. They not need to be economic costs only, but may also represent environmental and/or social costs bonded to local conditions. The variables E and W represent the amount of energy and water volume required to allow for the operation, respectively. This simple relation bears the inherent trade off relating energy and water use: whereas a high energy cost will imply the need to use additional water, this will cause the slurry flow rate to increase, given a fixed throughput goal. In particular, neglecting the importance of water will drive to the maximization of the energy efficiency and possibly the utilization fraction (Wu et al., 2010; Ihle and Tamburrino, 2012b), regardless the economic and/or environmental cost of water. On the other hand, if only water was the relevant element to save, then best operational scenarios, given the throughput, would be those with very high concentrations, and thus prohibitively high energy consumptions. In most locations, it is of uttermost importance to find a right balance between the use of energy and water in a conveniently defined way. However, such optimal values are not obvious and, in particular, depend on the unit costs of water and energy, c_W and c_E, respectively.

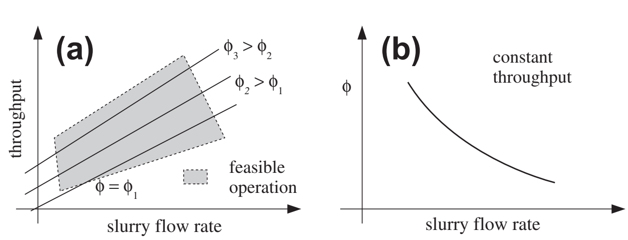

Fig. 1. Schematic representation of a typical operational guidelines, with ϕ representing the solids volume fraction. (a) Operational range, with the shaded region denoting the allowable operational points and (b) schematic representation of flow rate/volume fraction relation for a constant throughput value.

The components E and W may be expressed depending on the pipeline design approach. To assess the energy requirement, E, the hydraulics needs to be calculated and, in particular, the total energy consumption on a specific period. In pipeline flow, an energy balance between points 1 and 2 of a turbulent flow stream across the pipeline is given by Granger (1987):

$$\frac{p_1}{\rho g} + z_1 = \frac{p_2}{\rho g} + z_2 + JL_{12}, \quad (2)$$

with $J = \frac{f}{D}\frac{U^2}{2g}$ the hydraulic gradient. Here p_i and $z_i = z(x = x_i)$ are the line pressure and altitude at the route point x_i, assuming the flow going from point x_1 to x_2, distant by a tube length L_{12}, and g is the magnitude of the gravity acceleration vector. The last term of the right hand side of (2) represents the frictional pressure losses, which control the energy balance. There, the Darcy friction factor, f, is defined as $f = 8\tau_w/\rho U^2$, with τ_w, ρ and U the wall shear stress, slurry density and mean flow velocity, respectively, with D the pipeline internal diameter. It is customary for design purposes to slightly overestimate the energy consumption by incorporating a gradient factor, $\alpha_J > 1$, such that $J_{\text{design}} = \alpha_J J$. The unknown τ_w (or f), should be modeled considering the need to adequately represent the slurry segregation phenomena as well as the effect of the viscous characteristic of the slurries. Here, the Bingham model for the rheology is assumed (Chhabra and Richardson, 2008). There are several models to compute the frictional losses, including the Wilson–Thomas approach (Wilson and Thomas, 1985; Thomas and Wilson, 1987), which is based on an extension of the logarithmic velocity profile, and Blasius-like ones. The latter rely on the observation that many slurries flow within the smooth wall turbulence range, allowing the simple form $f \approx \alpha_f Re^{-\beta_f}$, where α_f and β_f (both positive) may possibly depend on the non-Newtonian characteristic of the slurry (Chilton and Stainsby, 1998; Darby, 2001). Here, the Reynolds number (Re) is defined in the usual way considering the Bingham plastic viscosity, η, as $Re = \rho UD/\eta$. The viscosity may be related to the concentration with the usual Krieger-type approach, $\eta \approx \mu(1-\phi/\phi_{SS})^{-\beta_\eta}$, with β_η a parameter and ϕ_{SS} the loose packing concentration. Some other models have been developed for the computation of pressure losses, accounting for particle stratification in the plane normal to the pipeline (Wasp et al., 1977; Abulnaga, 2002). However, when most of the particles are fine enough, the quantitative differences between these non-rheological approaches accounting for segregation and those purely based on the assumption of homogeneous, non-Newtonian slurry may be slight (Ihle and Tamburrino, 2012a). It is required that the pressure (p) should exceed the vapor limit, p_v, whose value at 20 °C is of about 2.9 kPa, or about 2.9% of the atmospheric pressure at this temperature. This operational restriction is thus inherited to the cost function (1) where, for every position (x) along the pipeline, it is required that:

$$p(x) > p_v. \tag{3}$$

On the other hand, the operational pressure, both at transient and steady state regime, should be kept within the pipeline design limits, defined by the applicable design code. For simplicity, this maximum value will be labeled as $p_{\max}$, and thus for every point along the pipeline the following restriction holds:

$$p(x) < p_{\max}. \tag{4}$$

To avoid the presence of particles deposited at the bottom of the pipeline, the flow velocity needs to exceed the deposit limit, U_d. As in the case of the computation of pressure losses, there are many models developed over the years to estimate it. Perhaps one of the best fitted ones for the iron and copper slurry particle size range is that of Poloski et al. (2010) which, extending the original scaling analysis by Shook et al. (2002), propose a relation between a densimetric Froude number, Fr, and an Archimedes number, Ar, as $Fr = \alpha_d Ar^{\beta_d}$, with α_d and β_d fitted as 0.59 and 0.15, respectively, for $Ar = \frac{4}{3} g d_{50}^3 (S-1)(\rho/\eta)^2 < 80$. Here, d_{50} and S are the median particle size and specific gravity of solids, respectively. The densimetric Froude number is defined as $Fr = U_d[gD(S-1)]^{-1/2}$. Other models for computing the deposit velocity are reviewed in Poloski et al. (2009).

The traditional approach for the identification of the minimal flow velocity condition is to identify the laminar–turbulent critical velocity, U_t. While in Newtonian fluids the simple condition $Re \gtrsim Re_c = 2100$ holds, in Bingham plastics, such critical condition is also a function of the ratio of yield-to-wall stress ratio, τ_y/τ_w or, similarly, a function of the Hedström number, defined as $He = \rho \tau_y D^2/\eta^2$, where the yield stress may be estimated as $\tau_y \approx \hat{\tau}(\phi_{SS}-\phi)^{-\beta_y}$, with $\hat{\tau}$ and β_y fit parameters (e.g. Heymann et al., 2002; Ihle, 2013a). Among the most regarded models for the computation of laminar–turbulent transition in slurry pipelines is that of Hanks (1963) (see also Wasp et al. (1977) and Abulnaga (2002)), which has been more recently adjusted in a simple empirical expression for $He > 10^5$ by Slatter and Wasp (2000) as $U_t = 26 \cdot (\eta/\rho D) He^{1/2}$. The minimum transport velocity, $U_{\min}$, may be therefore cast as the upper envelope of the deposit and laminar–turbulent transition curves. Considering a design factor $k_U > 1$, this corresponds to:

$$U_{\min} = k_U \max[U_d, U_t], \tag{5}$$

where it is noted that this expression is a function of the slurry volume fraction, ϕ, and typically has a local minimum at the intersection of the deposit and laminar–turbulent transition curves. In terms of the slurry flow rate, Q, feasible solutions must therefore meet the following lower limit restriction:

$$Q > \frac{\pi D^2}{4} U_{\min}. \tag{6}$$

Assuming that the pump station delivers the slurry at a pressure p_1, that the pipeline has a constant internal diameter and that the corresponding pressure is consistent with the restrictions (3) and (4), the required pumping power, $p_1 Q/\epsilon$, with ϵ the pumping efficiency, may be integrated over a period λT ($\lambda < 1$), to obtain the energy consumption over a period T with a system utilization λ as:

$$E = \frac{p_1 Q(\phi)}{\epsilon} \lambda T. \tag{7}$$

In (7), the concentration and the flow may not take arbitrary values. Besides the fact that E must fulfill the constraints (3)–(6) Q, ϕ and λ must be consistent with the required throughput goal, $\dot{m}$. The following solids conservation relation holds (Ihle, 2013a):

$$\dot{m} = S\phi Q \lambda \rho_W, \tag{8}$$

with ρ_W the density of the liquid phase (typically that of water). The consumed water volume, W, may be obtained from a mass balance in the system:

$$W = \frac{\dot{m} T}{S \rho_W} \left(\frac{1}{\phi} - 1 \right). \tag{9}$$

It is noted that (7) is a strong function of the total pipeline length, L through the pump discharge pressure p_1, whereas the water consumption, given by (9), is mostly controlled by the throughput and the solids concentration. If the throughput goal is known, the problem proposed herein is to obtain the lowest possible value of the cost function Ω that makes the hydraulic transport possible. In terms of the system variables, the problem is to find:

$$\Omega_* = \min_{\lambda, Q, \phi} \Omega, \tag{10}$$

given 1, 7 and 9, along with the constraints 3, 4, 6 and 8. In particular the optimization problem given by the expression (10) is subject to the unit cost parameters c_E and c_W. The computational cost required to solve this optimization problem depends critically on the number of operations required to evaluate the objective function Ω, which depends on the hydraulic approach used to compute the energy consumption (7) through the pressure losses. As in Ihle (2013a) and Ihle et al. (2013), to solve the present problem a Sequential Quadratic Programming algorithm using GNU Octave (SQP, Boggs and Tolle, 1995; Eaton et al., 2011) has been adapted (see also, Okamoto and Hirata, 2011; Brásio et al., 2011, and references therein).

The friction factor (f) and the slurry viscosity (η) have a nonlinear dependence with the Reynolds number and solids concentration, respectively, therefore rendering the optimization problem nonlinear. On the other hand, the constraints are not necessarily convex, as seen from the deposit velocity and energy curves shown in Ihle and Tamburrino (2012b) for a similar problem. In particular, in the computation of the minimum velocity (Eq. (5)), there is a distinct, non-smooth minimum that marks the transition from the dominance of the deposit velocity (U_d) to that of the laminar–turbulent transition limit (U_t).

Although convergence is not guaranteed because it depends on the initial guess of the algorithm – an inherent feature of gradient-based optimization algorithms (Eaton et al., 2011) –, for the cases analyzed herein, there were no significant difficulties to find optimal solutions of the minimization problem given by Eq. (10). In particular, this was checked varying the initial guesses for a subset of the selected problems, with repeatable results. Convergence was checked evaluating the objective function (1) at different points of the (λ, Q, ϕ)-space. In all the instances analyzed, the corresponding trial costs were found greater than the converged solutions. In particular, this is confirmed in Section 3, when comparing present results with typical operational conditions. The sequence of steps implemented is summarized as:

1. System parameter and topography definition (e.g. the values in Table 1, below).
2. Throughput ($\dot{m}$), energy and water unit costs (c_E and c_W, respectively) setting.
3. System constraint definition (Eqs. (3), (4) and (6)).
4. Initial guess for pipeline utilization fraction (λ), flow rate (Q) and solids volume fraction (ϕ).
5. SQP algorithm run to solve (10) in terms of the energy and water consumption (Eqs. (7) and (9), respectively), following steps 1–4. If convergence is not achieved, return to step 4.

As the three variables (λ, Q, and ϕ) are involved plus the possible number of iterations required to solve the hydraulics for every case, the optimization problem given by Eq. (10) is often hard to tackle using a brute force approach. Fig. 2 shows a typical run showing the feasible and unfeasible subspaces.

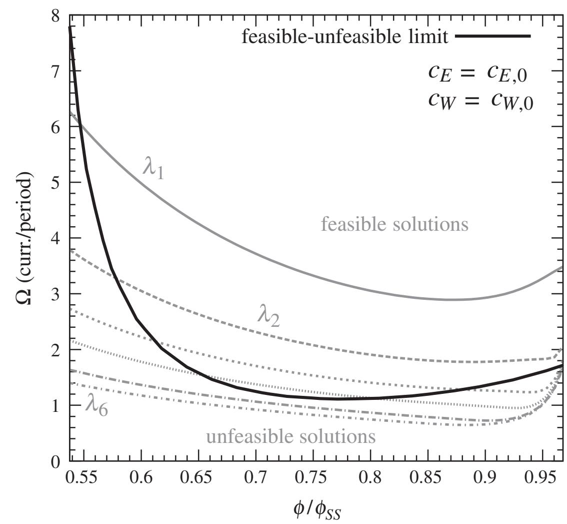

Fig. 2. Schematics of the structure of the cost function Ω, given by (1), in arbitrary currency units per period, for fixed energy and water unit costs (c_E and c_W, respectively). The x-axis shows values of the solids concentration by volume (see also Ihle, 2013a), scaled by the loose packing concentration, ϕ/ϕ_{SS}. The black solid line represents the limit between the feasible and unfeasible solution space. The area above the thick line represents feasible solutions of the optimization problem (10). The optimal solution corresponds to the minimum of such curve.

3. Example

3.1. Computational hypotheses

In the present section an example is developed for the case of a 12-in. nominal diameter iron concentrate pipeline. The slurry flows through a cross-country route, so that the restriction (3), related to the vapor pressure at the high points of the route, applies. As in common mineral processing plants, the present computations include a wide variety of throughputs ($\dot{m}$), ranging from 3 MTon/year to 6 MTon/year. A set of energy and water costs is also considered, with the corresponding set of computational hypotheses listed on Table 1.

3.2. Results and discussion

A key difference between the present optimization problem and usual design approaches for slurry transport systems is the ability to solve for the pipeline utilization factor, λ. Thus, when operating at relatively low throughput goals, the solutions given by (10) yield a operational fraction of the time lower than the typical 95–98%, corresponding to usual system design conditions (Fig. 3a). It is noted that at a pipeline utilization $\lambda = \lambda_{max} = 0.95$ and given the concentration, the flow rates that result from the mass balance in (8) need to be higher than those with $\lambda < \lambda_{max}$, and thus the values of the cost function Ω. In particular, increasing the concentration and the flow rate beyond a certain value will increase the cost function and thence the associated optimal value, as depicted in Fig. 2 and discussed elsewhere (Ihle and Tamburrino, 2012b; Ihle, 2013a). The corresponding concentration (Fig. 3b) and flow rate (Fig. 3c) also show the distinct constant-to variable trend resulting from the part time-full time operation transition. It is observed from the present results that, at constant pipeline length and diameter, the sorting of the different cost scenarios depend on the relative importance of water and energy unit costs. In particular, it is noted from Fig. 3a that

Table 1
Computational hypotheses and input values.

Name	Description	Value
(c_E, c_W)	Combinations of energy and water unit costs, in USD/MWh and USD/m^3, respectively	(30, 2), (75, 1), (120, 4), and (150, 6)
d_{50}	Median particle diameter	30×10^{-6} m
D	Pipeline inner diameter (API X65 sch. 80)	12 in (nominal)
f	Friction factor pressures loss model	Darby, 2001
k_U	Minimum velocity factor	1.25
L	Pipeline length	100 km
$\dot{m}$	Pipeline throughput range (dry)	3–6 MTon/year
p_2	Boundary condition for pressure at $x = L$	1 MPa
p_{max}	Maximum line allowable pressure	ASME B31.3 code
S	Solids specific gravity	5.0
α_J	Hydraulic gradient factor	1.1
β_η	Exponent for the Krieger-type viscosity relation $\eta = \mu(1 - \phi/\phi_{ss})^{-\beta_\eta}$	2
β_y	Exponent for yield stress model	2
ϵ	Pumping efficiency	0.7
ϕ_{ss}	Loose packing (settled solids) concentration	0.465 (Ihle, 2013a)
λ_{max}	Maximum possible utilization factor	0.95
$\hat{\tau}$	Constant for the yield stress model, $\tau_y = \hat{\tau}(\phi_{ss} - \phi)^{-\beta_y}$	0.038 Pa

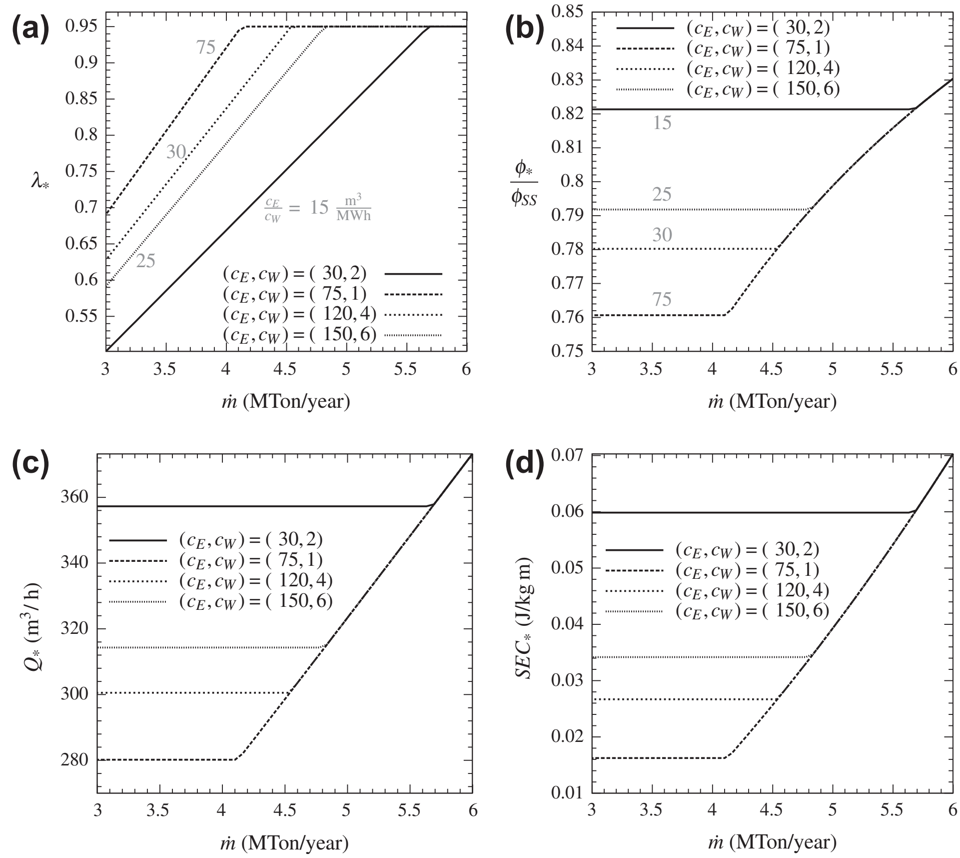

Fig. 3. Results obtained solving the optimization problem (10) for the different cost scenarios considered, in terms of the system throughput, $\dot{m}$. (a) Pipeline utilization fraction; (b) solids volume fraction, normalized by the solids settled concentration, ϕ_{SS}; (c) slurry flow rate and (d) specific energy consumption. The unit cost values for energy and water, c_E and c_W, are expressed in USD/MWh and USD/m^3, respectively. The gray numbers represent the unit cost ratio, c_E/c_W, in m^3/MW h.

higher energy/water cost ratios are related to higher system utilization ratios for a constant throughput. On the other hand, higher water costs imply the need to increase the flow rate and the volume fraction operating, however, a lower portion of the total available time. Although the unit cost ratio (c_E/c_W) gives an indication of the optimal curve trends, it gives a somewhat biased picture of trends: the energy/water relative importance should instead be seen as a dimensionless ratio between the first and second terms on the right hand side of (1). Differently from the referred ratio presented herein, which is reasonable in existing pipelines (i.e., given the diameter and the length), a broader analysis of the relative effect of energy and water costs for design purposes should also include the pipeline geometry.

An interesting implication of this optimization scheme is that the specific energy consumption, defined as the required energy to transport a unit mass of dry solids, $SEC = \frac{p_1 - p_2}{SL\phi\rho_W}$ (Wilson et al., 2006; Wu et al., 2010), now depends on the water/energy cost scenario, and thus represents a generalization of the energy-efficient transport condition previously proposed. The corresponding set of curves in the context of the present example are shown in Fig. 3d. Upon seeing the specific energy consumption in the light of the c_E/c_W ratio, it is observed that higher values are related to lower relative costs of water. This is a consequence of the fact that the specific energy consumption is insensitive to the use of water. Thus, at constant $\dot{m}$, if the water is relatively more expensive (i.e., c_E/c_W drops), then the optimal parameters are pushed towards a more intensive use of energy to reduce the water consumption, therefore implying a higher energy consumption in general and, in particular, per unit of dry solids.

The set of optimal values depicted in Fig. 3 may be also represented in terms of their energy line, corresponding to the term $p/\rho g + z + U^2/2g$. This is shown in Fig. 4, where it is seen that the low tonnage case, corresponding to the throughput $\dot{m} = 3$ MTon/year, (Fig. 4a), presents differing solutions for the hydraulic gradient depending on the values of c_E and c_W. In this case, the smallest value of the ratio c_E/c_W (15 m^3/MW h), corresponding to the largest incentive for water saving, is bonded to the highest hydraulic gradient (8.2 m$_{\text{slurry}}$/km), whereas the opposite holds for the highest value of such ratio (75 m^3/MW h), where it is best to use as little energy as possible, at the expense of additional amounts of water or, equivalently, lesser concentrations. In contrast to Fig. 4a and b depicts a higher tonnage scenario ($\dot{m} = 6$ MTon/year) where, for all the cost instances, there is a single optimal solution for the three different cost combinations considered. This is explained by the fact that at high tonnages the system reaches an optimum at the maximum possible utilization rates (Fig. 3a), and thence the optimal flows are merely obtained from the mass conservation statement (8), provided any additional throughput increase will be controlled by the requirement to spend additional pumping power, which is proportional to Q^3. This may also be seen in Fig. 3a and b, which show that for a given throughput both the optimal volume fraction and flow rate are monotonically decreasing functions of the ratio c_E/c_W. It is therefore a matter of finding a high enough tonnage to convert the optimization problem (10) in a problem controlled by energy consumption and mass conservation alone. This is a natural consequence of pushing the transport capacity of the pipeline towards an upper limit. However, at design stage, a trade-off between the

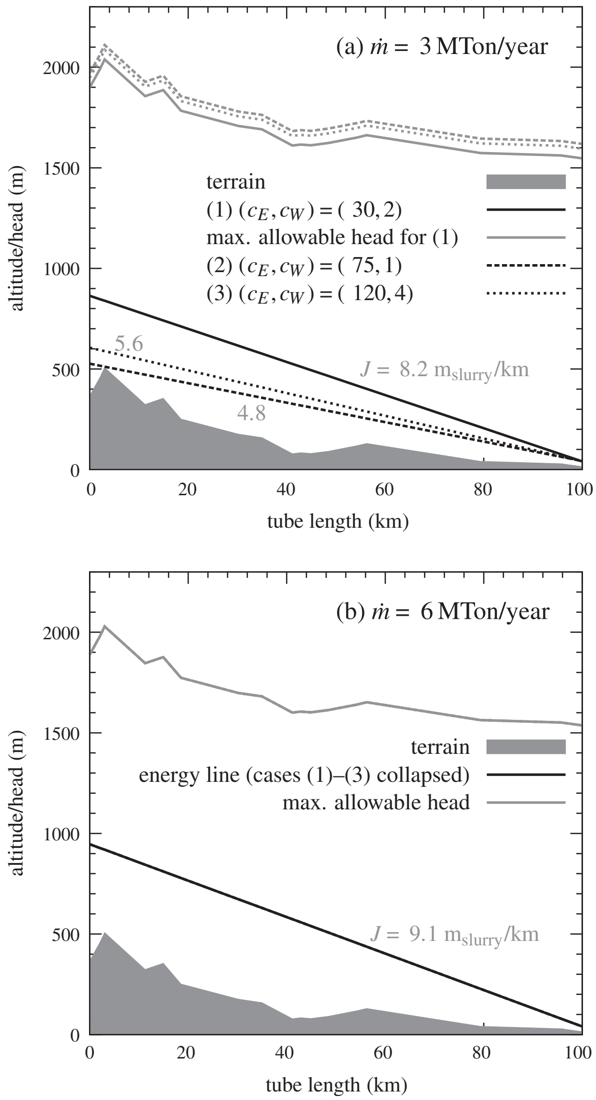

Fig. 4. Energy line for the optimal results corresponding to (a) a throughput $\dot{m} = 3$ MTon/year and (b) $\dot{m} = 6$ MTon/year. The gray lines, labeled with the same line type as their corresponding cost scenarios, represent the maximum allowable head according to ASME B31.3 code. The gray text denotes the hydraulic gradient, J, corresponding to each condition, in meters of slurry column per pipeline kilometer.

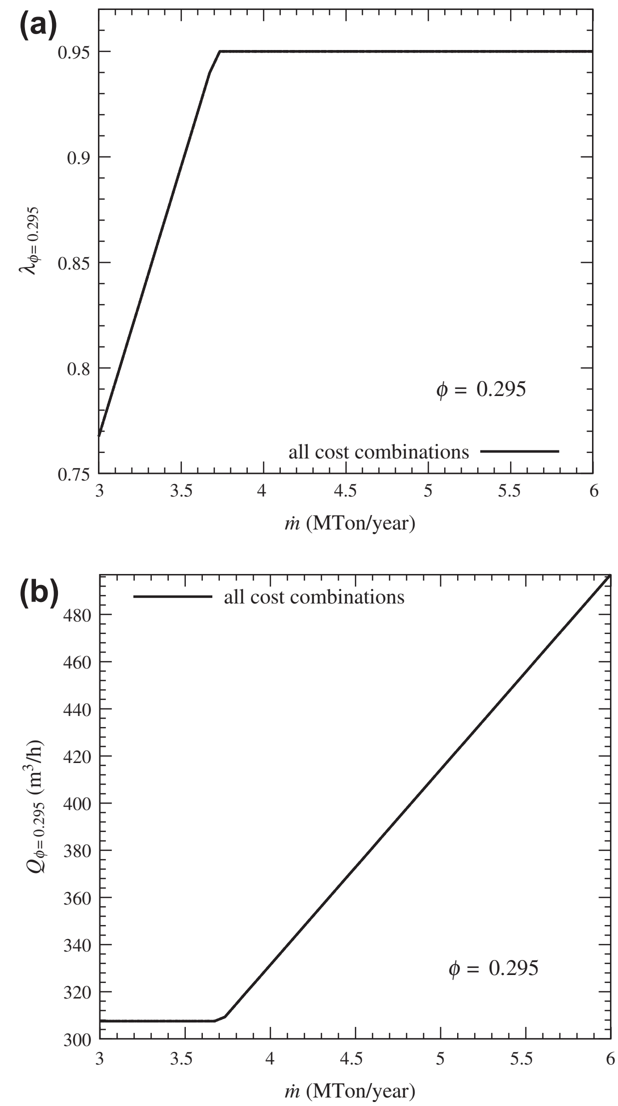

Fig. 5. Results for fixed a volume fraction corresponding to typical operational conditions ($\phi = 0.295$), with the same pipeline geometry and slurry characteristics as described in the present optimization routine. (a) Pipeline utilization factor (λ) and (b) flow rate (Q).

potential for combined energy and water saving and the pipeline investment appears, thus rendering the pipeline diameter an additional key variable to be considered in the analysis during the project phase.

It is instructive to compare the present results with typical operational conditions. To this purpose, consider a slurry volume fraction $\phi = 0.295$, equivalent to solid fractions by weight of 0.637 and 0.677 for values of the specific gravity of solids of 4.2 and 5, representing common figures of copper and iron concentrate, respectively. An unbiased comparison could only be made at equal throughputs, thus requiring to adjust the utilization ratio, λ, to fulfill the mass conservation Eq. (8). A consequence of fixing the concentration in the optimization problem (10) is that, for a given throughput, the water utilization, given by (9), becomes fixed, and therefore the optimization problem becomes entirely controlled by the energy consumption through (7) and the aforementioned mass balance (8). As the energy consumption is a monotonically increasing function of the flow rate (provided the solids concentration remains fixed), then the maximum values are, regardless the energy and water unit costs, located at the minimum possible flow rates, i.e., when $Q = \frac{\pi D^2}{4} U_{\min}$ in (6). Fig. 5 shows both the corresponding pipeline utilization ratio and the flow rate. Comparing the resulting utilization factors between the case $\phi = 0.295$ (fixed) with those concerning the less biased optimization scheme reveals that full system utilization (at $\lambda = \lambda_{\max}$) occurs, in the fixed concentration instance, for lower throughputs than in the optimized case. On the other hand, the cost-dependent set of optimal slurry concentrations depicted in Fig. 3 are, in all the cases analyzed, significantly higher than the reference value of 0.295. In particular, for $c_E/c_W = 15, 25, 30$ and 75 m^3/MW h, the optimal values for ϕ obtained (ϕ_*) are 0.38, 0.37, 0.36 and 0.35, respectively, implying that only for extremely high energy costs in relation to those of water, optimal values close to those typical in many long distance pipeline operations would be found. As a consequence of this result, the corresponding flow rates are much higher on the fixed concentration case than on those optimized.

The resulting energy lines for the fixed concentration case are depicted in Fig. 6, where, as the result of the requirement to simply save energy, the resulting energy tend to stick to the lowest

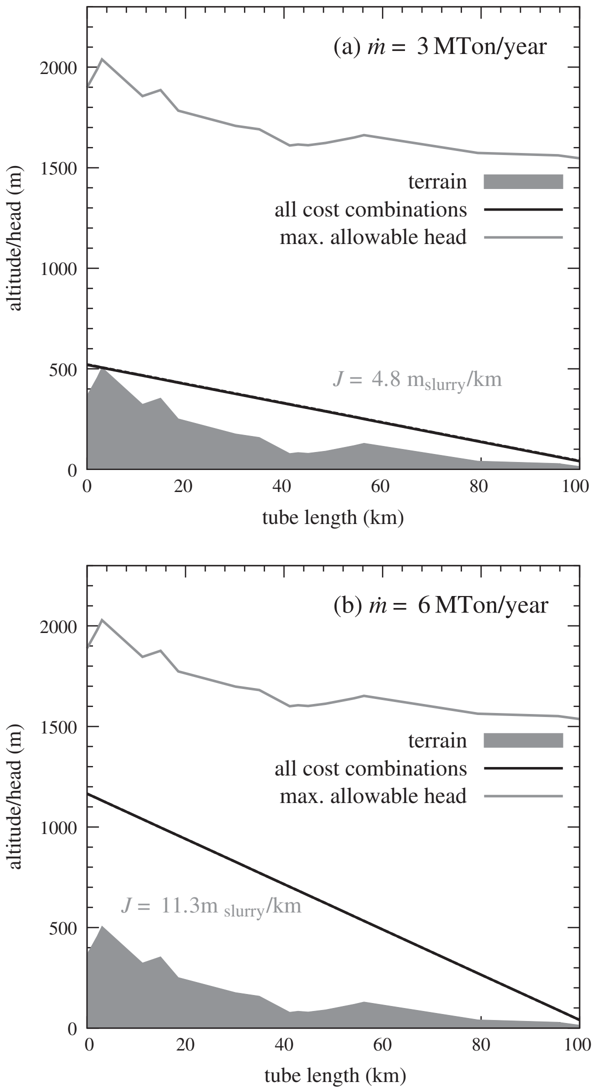

Fig. 6. Energy line when the volume concentration is fixed to $\phi = 0.295$ (a) a throughput $\dot{m} = 3$ MTon/year and (b) $\dot{m} = 6$ MTon/year.

possible slope by solely adjusting the flow rate, whereas in the unbiased optimization scheme some higher-than-minimal hydraulic gradients are required in view of sufficiently high water costs. It is remarkable that the best hydraulic gradient, of 11.3 m_{slurry}/km (Fig. 6b), is higher than the highest optimal one with the unbiased optimization (9.1 m_{slurry}/km as shown in Fig. 4b), despite in both cases the system was operating at the maximum utilization fraction ($\lambda = 0.95$). This gives a clear indication of the considerable utility of including the solids concentration in the optimization scheme.

The overall result of the optimization procedure, when compared to that with a fixed concentration, is depicted in Fig. 7, where depending on the throughput and the cost combinations, multimillion dollar savings may be reached, whereas this may also be combined with tight input variable follow-up directives, including for instance the slurry properties (Ihle et al., 2013), for reaching an improved use of resources.

4. Final remarks

The present results of the optimization scheme and the set of related constraints, have some distinct features, when compared to common operational conditions. In particular, the present optimal results show a marked tendency to operations at lower pipeline utilization ratios, higher concentrations and lower flow rates than in the typical case.

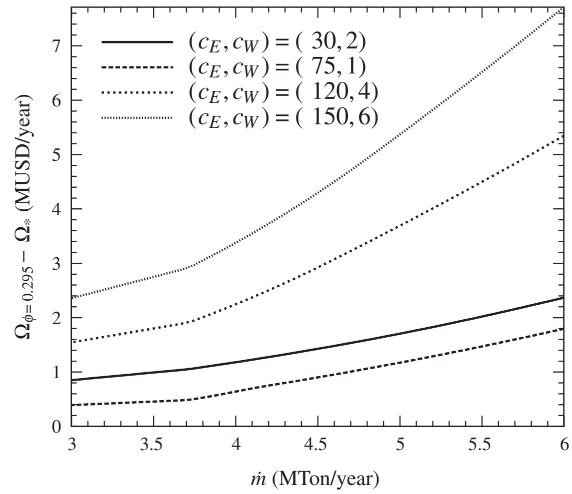

Fig. 7. Resulting overall differences between the present optimal and fixed concentration solutions for different unit cost scenarios $\Omega_{\phi=0.295} - \Omega_*$, in terms of the system throughput, $\dot{m}$.

Regarding the implicit suggestion to raise the volume fraction, an obvious question is whether it is actually possible to do so. The answer depends on the particular conditions of the pipeline, and not only the hydraulic feasibility should be considered, but also the additional operational constraint that shutting down a long distance line with a considerable larger amount of solids in it should also be assessed and analyzed in the context of versatile facilities prepared to handle conditions at specific low points where concentrate plugs may be formed (Ihle, 2013a). Although the hydraulics given here say it is possible, the local conditions and infrastructure impose an in-depth revision of potential additional constraints.

Most of the curves presented herein are related to various throughput instances. The relatively wide range of the latter reproduced herein is intended to represent the highly variable character of many mining plans – whose possible particular forms are not relevant for the purposes of the present work –, where the mapping between the pipeline utilization, the flow rate and the slurry concentration out of a dynamic programming of the system throughput is straightforward. In this regard, given its relatively modest computational cost, the proposed optimization scheme may blend smoothly with virtually any real time plant programming scheme. However, its success and flexibility is strongly dependent on the pipeline diameter choice. Present results suggest that operational scenarios will only be amenable to be set in terms of economic and environmental cost fluctuations – energy, water, carbon footprint, etc. – if the pipeline diameter is large enough to allow partial utilization fractions, and thus actively enter in the optimization problem given by Eq. (10). In particular, operating at lower pipeline utilization ratios than in usual plant designs have the inherent requirement of having larger holding facilities, which by itself represent a whole different design and operational rationale, and triggers the need to extend the present optimization problem to one involving infrastructure as well.

5. Conclusions

In this paper, an optimization problem for long distance slurry transport using pipelines, involving the consideration of water, energy and perhaps environmental costs, has been proposed to expose the necessity to switch to a new design and operational paradigm allowing to include variable operational scenarios depending on the values of weighting parameters expressed as unit cost values. Despite that the present quantitative results are inherent to a particular choice of input parameters, there is a marked tendency to part-time operation, relatively lower slurry flow rates and higher concentrations than in standard systems. This suggests a different way to tackle the design and operational planning of this resource-intensive kind of productive facility.

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