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The least energy and water cost condition for turbulent, homogeneous pipeline slurry transport

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ABSTRACT

The efficient combined use of water and energy in long distance slurry pipelines is analyzed in light of the total cost function resulting from an energy and mass balance. Given a system throughput and a set of common slurry and flow properties associated with long distance cross country pipelines such as Krieger-type rheology and smooth wall turbulent flow with small yield-to-wall stress, the minimum cost condition is obtained at the minimum feasible transport mean velocity. This condition has been found irrespective of the particular value of the dissipation-to-pump station location difference, provided the required pumping power is positive.

Contents

1. Introduction

Long distance pipelines are often a cost-effective means of transporting a wide variety of ores and tailings between remote locations (Jacobs, 1991; Abulnaga, 2002). Considering that long distance slurry transport requires massive amounts of energy, the concept of energy efficiency in this kind of infrastructure (Wilson et al., 2006) is highly relevant. Motivated by the additional and recurrent constraint relating mining operations with water scarcity, the well-known problem of energy efficiency has been recast into a problem of minimum cost (Ihle, 2013; Ihle et al., 2013), which includes the cost of water. This new approach opens the question on whether the conditions for energy efficiency (Nguyen and Boger, 1998; Sofrá and Boger, 2002; Ihle and Tamburrino, 2012) are the same of those minimizing the sum of energy and water cost. The finding from the solution of a large-scale optimization problem

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that the minimum transport costs are apparently related to the minimum velocity (Ihle, 2013, Table 1), suggests to analyze in more detail the role of such condition. Although it has been previously suggested that the optimum concentration of solids increases with the throughput (Nguyen and Boger, 1998; Sofrá and Boger, 2002), and decreases with the velocity (Nguyen and Boger, 1998; Sofrá and Boger, 2002; Wu et al., 2010; Edelin et al., 2015), such experimental observations do not give a weight to the use of water. However, if water is considered, it has been shown that the optimal concentration is indeed an increasing function of the throughput (Ihle et al., 2014a). In this paper, a dimensionless formulation of the cost function is used to analyze the various possibilities of the cost and flow characteristics. Considering flow conditions and characteristics typical of fine-graded slurries such as bauxite, copper and iron concentrates, it is shown that it is precisely the minimum feasible velocity that which minimizes the combined water and energy cost. The result has been extended to cross country pipelines featuring an energy dissipation point or an elevated discharge.

2. Problem description

Consider an operating slurry transport system of length L with known internal diameter (D) where the throughput (G), defined as the dry solid rate, along with route and slurry properties are known. The total energy and water cost per unit time may be expressed as:

$$\Omega = c_e P + c_w Q_w, \tag{1}$$

where c_e and c_w represent the unit costs of energy and water, respectively. The variables P and Q_w are the pumping power and the water flow required to allow for the dispatch of the solids, respectively.

Assuming a final atmospheric discharge and neglecting minor singular pressure losses (except those intended to avoid column separation, consisting of the appearance of a gas phase in the slurry column, as explained below), the required pumping power is calculated using the energy conservation and the Darcy–Weisbach equation as:

$$P = \left(H_d - z_0 + \frac{8}{\pi^2}\frac{fLQ^2}{gD^5}\right)\frac{\rho g Q}{e}, \tag{2}$$

where f is the Darcy friction factor, $f = \pi^2 D^4 \tau_{\text{wall}}/2\rho Q^2$, with Q and ρ the volume flow and density of the solid–liquid mixture. Here, D is the pipe internal diameter, g is the magnitude of the gravity acceleration vector, τ_{wall} the pipe wall shear stress and e is the overall efficiency of the pumping system. Here, z_0 is the altitude of the pump station (referred to a datum) and H_d is total singular energy consumption head required to ensure that at every point of the route the line pressure would exceed the vapor value to avoid column separation and the potentially harmful consequences of related flow transients (Bergant et al., 2006). The head loss H_d may be alternatively expressed in terms of a dimensionless coefficient (k_d) as $H_d = \frac{8k_dQ^2}{g\pi^2D^4}$. A schematic of the importance of H_d is shown in Fig. 1, where the lines represent the hydraulic head, $E = p/\rho g + z_t + v^2/2g$. Here, z_t, p and v are the topographic altitude, line pressure and mean flow velocity, respectively. In long distance pipeline systems, commonly $v^2/2g$ is negligible in front of $p/\rho g$.

Fig. 1a and b shows a schematic of the hydraulic head line that minimizes the energy and water cost for the cases of flat or very low topography. In both cases the energy line remains unchanged. However, if the topography is high enough the former energy line might cross it. As the absolute pressure must be greater than the vapor value, the pipeline extension that crosses the topography under this operational scenario must then be at the vapor pressure. This is denoted by the dashed line in Fig. 1c. To ensure that the whole energy line will not cross the topography in a fixed diameter pipeline, there are two possible mechanisms. One is to increase the volume flow, which effectively increases the

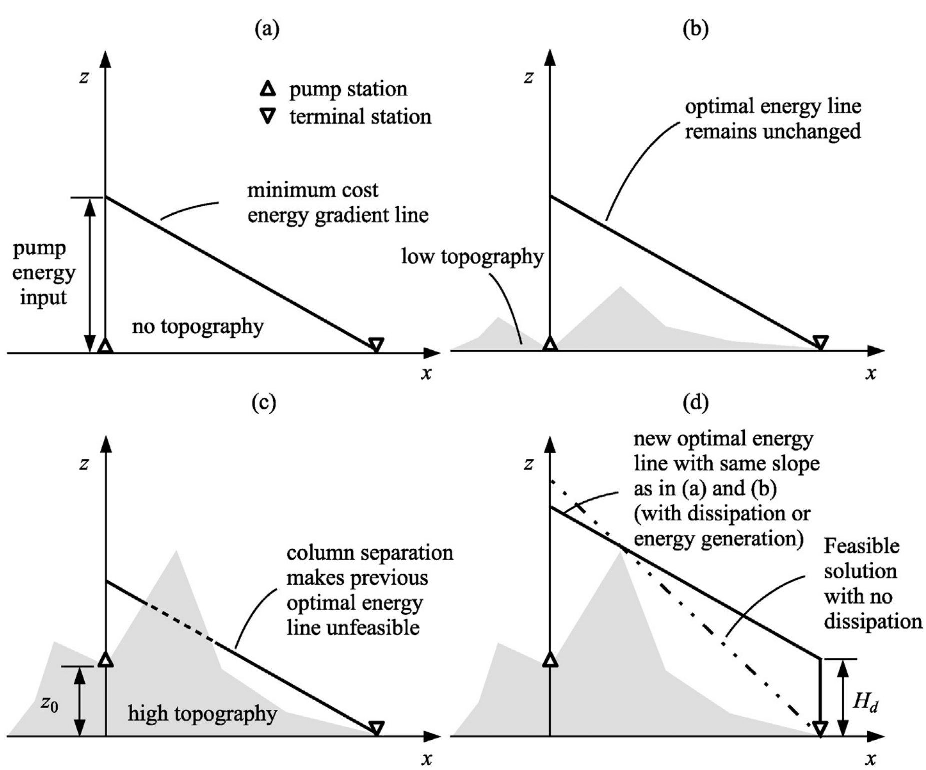

Fig. 1. Schematic of the hydraulic head, E, denoted by lines, in terms of the tubelength distance, x. The shaded area represents the topography. (a) Flat topography. (b) Topography with no influence on the optimal condition. (c) Topography with influence on the optimal energy line. (d) A correction to the optimal condition in (c), incorporating a singular head loss, H_d.