Pipeline Hydraulic Transport of Biomass Materials: A Review of Experimental Programs, Empirical Correlations, and Economic Assessments

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Abstract

Pipeline hydro-transport, an economically viable means of delivering large volumes of biomass, can replace conventional modes of transport - road, rail, and river - to improve the economy of pulp and paper mills, as well as bio-based energy facilities. This paper is a review of experimental and theoretical studies conducted by various sectors on the transport of wood and non-wood biomass-water mixtures (slurries) in pipes. The aims were to collect technical challenges, governing mechanical equations, and associated economic issues, as well as to identify the gaps in knowledge in the area. There have been several experiments conducted on pipeline hydro-transport of wood chips over a wide range of pipeline materials, lengths, and diameters. However, pipeline transport of non-wood agricultural residue slurries, as well as the performance of the centrifugal slurry pump handling such mixtures, has recently been investigated in a single lab-scale pipeline facility. Several researchers have proposed empirical correlations to estimate friction loss in wood chip slurries flowing in pipes and also recommended technically and economically optimum pumping velocities. Those correlations, however, are reported to come with noticeable deviations from one

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another and from experimental measurements. One empirical correlation has been also proposed to predict, with an uncertainty of less than 10%, the longitudinal pressure gradients in pipeline hydro-transport of agricultural residue biomass. All the experimental measurements and empirical correlations based some studies on the economic feasibility of pipelining wood chip-water mixtures. These studies proved the concept of economy of scale to be highly applicable to biomass pipeline systems.

Keywords: Biomass, wood chip, agricultural residue, pipeline, hydro-transport

Nomenclature

1. Introduction

Hydraulic transport (hydro-transport) of solids in pipes has been the subject of investigation since the turn of the last century. The first person to conduct a systematic investigation on solid-liquid mixture flows through a 25 mm horizontal pipe was Nora Blatch in 1906 [1]. Since then, particularly owing to the improvements in centrifugal pump design and the advances in solid-liquid mixture flow knowledge during the 1960s [2], several short and long solid-liquid mixture pipelines have been constructed to hydraulically transport a variety of solids, from coal to limestone to complex bitumen. The technical and economic advantages of pipeline hydro-transport have encouraged various sectors to consider replacing conventional modes of transport, e.g., road, river, and rail, with pipelines for long-distance transport purposes. Major advantages include benefits from economies of scale in the construction of the pipeline and associated equipment; large transportation volume (e.g., 2.273 Gt y^{-1} of phosphate concentrate [1, 3]); excellent safety record (fewer than two incidents per 10,000 km of pipeline reported per year [4]); continuous operation; reduced in-transit inventory; low labor content; independence from weather, road, and terrain conditions;

possible reuse of carrier liquid; and the possibility of sharing between more than one companies [5].

While, to the authors' best knowledge, there is no large-scale long-distance biomass pipeline in operation at the moment, the pulp and paper industry uses hydro-transport technology for wood pulp fibres for on-site processing over short distances [6-9]. The pulp and paper industry has also conducted some laboratory-scale research projects on wood chips pipeline hydro-transport for feedstock supply purposes [10-12]. Besides the pulp and paper industry, pipeline hydro-transport of biomass, more specifically lignocellulosic biomass, is now receiving new interest as an alternative means of delivering biomass to bio-based plants [13-20] that can potentially reduce the cost of feedstock delivery [13] and enable bio-based energy facilities to reach higher capacities.

Wood pulp fibre is not a natural biomass but a mechanically or chemically processed biomass, and, therefore, its hydro-transport is not reviewed here. This paper instead reviews the literature published on the pipeline hydro-transport of unprocessed biomass in the pulp and paper industry as well as in the bio-based energy sector. The literature is reviewed in chronological order and is classified into experimental programs, empirical correlations, and economic assessments. All the costs reported in the economic assessments section have been inflated to the 2014 U.S. dollar. Table 1 lists the research activities conducted in this field and reviewed here. The objectives of this review are to understand the technical challenges and mechanical limitations as well as the economy of biomass pipeline hydro-transport, also to identify gaps in the knowledge of biomass pipeline hydro-transport for future research.

Table 1

2. Experimental Programs

2.1. Introduction

The design and operation of solid-liquid mixture (slurry) pipelines is a complex problem where, as it was listed by Nardi in 1959 [34], as many as 32 variables have to be taken into account before someone designs a pipeline to successfully pump solids. These complexities have been previously addressed while pipelining conventional solids such as coal [35], phosphates [3], iron ore [36], bitumen [37], rock, sand, and stone [38, 39]. Several researchers studied such complexities in biomass slurry pipelines as well, all non-commercial practices, though.

In this section, experimental investigations on slurry pipelines for wood chips and agricultural residue biomass are examined over a wide range of variables. The biomass pipeline projects reviewed here cover a wide range of biomass physical properties and pipeline operating conditions, including pipeline materials of aluminum, clear plastic, acrylic, and steel; pipeline lengths of 25 to 1220 m; pipeline diameters of 50 to 300 mm; moisture contents (*MC* - mass fraction of water in the solid) of 50 to 79%; particle diameters (d_{50}) of 1.9 to 28.4 mm; slurry solid volume contents of 1.8 to 47%; and biomass-water mixture velocities of 0.5 to 5.0 m s^{-1}. The advantages specific to biomass pipelines include all usable (wood and non-wood) species transported without losses related to truck delivery or moving wood on river drives; possible transportation of small-diameter wood, as well as bark, needles, and stumps (now wasted) for use at the mill; the elimination of log storage, handling, and protection; and wider choice for the location of new mills [5, 26]. Practical experience with these feedstocks would be of great help in the design of new pipelines or modification of existing systems.

2.2. Wood Chip-Water Mixtures in Pipes

Elliott and de Montmorency [10, 21] at the Pulp and Paper Institute of Canada (PAPRICAN, later merged with two main forest sector research institutes, FERIC and Forintek Canada Corp., to form FPInnovations) were the first to install a laboratory-scale experimental facility to study the hydro-transport of wood chips in pipes. The velocities used range from 1.2 to 3.0 m s^{-1} and the mixture ranged up to 48% by volume of wood [5]. The facility was composed of 160 m of 200 mm diameter aluminum pipe, and the chips were spruce and balsam fir, with d_{50} of 6.4 mm that, at a fully saturated condition, attained a moisture content of 68% to 70% and density of 1030 to 1060 kg m^{-3} [10]. Elliott [21] observed a deterioration (also referred to as degradation or particle size reduction) caused mainly by the pump and reported the production of wood chips smaller than 12.7 mm to be four times more by weight compared to control chips from the original batch after four hours of circulation. The optimum mixture solid volume content was reported to be about 30%, since at a solid volume content of 35% the pump power consumption began to increase slightly and at 47% the mixing operation became erratic because the equipment was not designed for such a heavy mixture. Considering pressure drop measurements, Elliot and de Montmorency [10], using a pressure drop-velocity plot, showed that with increasing velocity the curves corresponding to the mixtures above a solid volume fraction of 20% go through a minimum of friction loss, where chips along the bottom start to build up toward plugging conditions. Afterwards, the curves straighten and become parallel/close to the pure water line where chips are in complete suspension. This research work stimulated similar experimental studies in the United States [12, 28, 30] and the Soviet Union [25].

The research and development section of the Shell Pipeline Company [23] studied hydro-transport of wood chip-water mixtures in a closed-circuit pipeline facility of 1220 m length and 200 mm diameter in Houston, Texas, U.S.A. The results were inconclusive and the system was later dismantled; further experiments were conducted on shorter and smaller clear plastic pipelines 50 mm in diameter. The results, however, were proprietary and not released [22].

Faddick [11] conducted an experimental investigation on wood chip-water mixtures on a 100 mm diameter pipeline. Later, he tried to simulate the pipeline hydro-transport of wood chips using uniform-sized plastic chips instead [30] (discussed in a subsequent section).

To verify the feasibility of the concept of wood chip hydro-transport and to determine the empirical laws relating various variables, Brebner [24] performed a series of experiments on a test circuit that was made up of 120 m of 100 mm diameter aluminum pipe. He used standard jack pine and spruce chips with d_{50} of 6.4 mm, which at fully saturated conditions attained a moisture content of 70% and density of 1150. Considering slurry flow regimes, Brebner observed three regimes at velocities between 1.5 and 4.5 m s^{-1} consisted of ″suspension″ for solid volume contents below 5%, ″discontinuous sliding bed with saltation″ for solid volume contents between 5% and 12%, and ″continuous sliding bed″ for solid volume contents above 12%. In the latter, chips were physically interlocked while loose chips progressed at a slightly faster rate above the sliding bed.

In another attempt to transport wood chips by pipeline, the Pulp and Paper Research Institute of Canada established a pilot-scale pipeline (Project DC-302) in Marathon, Ontario, beside one of Canada's pulp mills [5, 26, 27]. The pipeline was 610 m long, U-shaped, and comprised of a 150 mm diameter aluminum pipe, as well as 200 and 250 mm diameter steel pipes with two inclined sections at 10 and 20 degrees to simulated extremes in terrains. Equipment for the construction of the experimental facility was provided by ten companies (two major Canadian railroad companies, a construction and engineering design firm, a pipeline company, and six pulp and paper producing companies). Pumping pressures, pump speeds, flow rates, pressure drops, concentrations, pipe wear (using radioactive sections in the two steel lines), and water pH were monitored, recorded, and analyzed at the rate of 17 data every two seconds over 10 weeks. PAPRICAN concluded that ordinary commercial chips can be sent in a water slurry through a pipeline at velocities of 1.2 to 3.0 m s-1 and in mixtures up to 40% by volume of chips. At these velocities and concentrations, a 200 mm diameter pipeline can carry hundreds of tonnes of wood every 24 hours. The amount of wood damage for later mechanical pulping or sulfite pulping in pulp production procedures was found also to be slight, even after long transport. The detailed findings of the research project are confidential.

The Georgian Research Institute of Forest Industry (GrusvNIILesprom.) proposed a steel pipeline; 300 mm diameter and 80-120 km long, to be laid parallel to the Ingur River for the transport of wood chips to the pulp and paper combine at 1.6 m s^{-1} velocity [25]. To study the technical and economic feasibility of the proposed project, the research institute built a model gravity-fed steel pipeline system, 150 mm in diameter and 48 m long and wood chip-water mixtures with consistencies of 5 to 20% by volume at flow velocities of 1.0 to 2.5 m s^{-1} where used in the investigation. A bunker of wood chips with an electrically-driven screw feeder and a tank of water with a funnel were used to convey wood chips and water into the pipeline, separately, and also to adjust the wood chip to water ratio. The experiments showed that with an increase in mixture flow velocity, specifically beyond 2.2 m s^{-1}, the hydraulic characteristics of the flow improve. The research institute concluded that ″pipelines are fully suitable for the transport of wood chips in water suspensions″. The institute also recommended the application of steel pipes lined with plastic because of favorable hydraulic and economic indications.

Wasp et al. [28] conducted an experiment on conveying wood chips with a density of 1130 (fully saturated) and dimensions of 19 mm×12.7 mm×2.5 mm through a 200 mm diameter pipe at 3.0 m s^{-1} velocity. They applied the homogeneous-heterogeneous model [40] (see section 3, Eqs. 5 and 6) to identify the flow regime and mixture solid volume content across the pipe cross section.

Soucy [29], using 150 mm diameter acrylic pipes, conducted a series of experiments to measure the pressure drop of wood chip-water mixtures in pipes. Soucy's data were later used by Faddick [30] and Gow [12].

In 1962, the Montana State University entered into a cooperative aid agreement with the U.S. Forest Service to conduct a series of technical and economic analyses to establish criteria to design, construct, and operate wood chip pipeline systems to feed the pulp and paper industry [12, 30, 41]. As a part of this study and to simulate the pipeline hydro-transport of wood chips as well as investigate friction loss parameters, Faddick [30] transported uniform-sized plastic chips of densities of 920 and 1050 and dimensions of 12.7 mm×9.5 mm×2.5 mm through 75 mm and 100 mm diameter and 210 m long acrylic pipes. Later, Gow [12] modified Faddick's laboratory pipeline system to study wood chip-water mixtures and correlated experimental friction loss data over a range of mixture velocities, pipe diameters, wood chip sizes, and mixture solid volume contents. The use of lodgepole pine wood chips with d_{50} of 9.5 mm, a fully saturated moisture content of 50%, and a density of 1015 resulted in the mixture velocity's being limited to 3.3 m s^{-1} and 1.3 m s^{-1} through 100 mm diameter acrylic plastic and 150 mm diameter aluminum pipes, respectively. Gow's investigation was directly comparable to Faddick's experimental data [11] (the two experiments were conducted with a 100 mm diameter pipe). Gow concluded that at a given mixture velocity, the friction factor increases in magnitude with increasing solid volume content. Also at a given mixture velocity and solid volume content, the friction factor decreases with increasing pipe diameter. However, Gow noted the dependence of friction factor on pipe diameter was non-linear for high solid volume contents and insignificant at high velocities. An abrupt change was also observed in friction factor in which the corresponding velocity (critical velocity) depended on mixture solid volume contents and was due to the change in the mode of transport of wood chips from ″heterogeneous discontinuous sliding bed with saltation″ to ″continuous sliding bed.″ This study employed the terms ″pseudo-laminar″ and ″pseudo-turbulent″ to refer to sliding bed and saltation flows, respectively, to distinguish these phenomena from classical laminar and turbulent pipe flows.

Hunt [22] studied the hydro-transport of wood chip-water mixtures using elongated oblong plate-shaped lodgepole pine wood chips with d_{50} of 28.4 mm and approximate density of 1000 to 1050. He used 200 mm and 300 mm diameter and 91 m and 183 m long steel pipes in order to scale up the experiments conducted on 75 mm, 100 mm, and 150 mm diameter pipes and to examine the applicability of the extrapolation approach to friction loss correlations proposed by others [12, 30]. The friction loss correlation proposed by Hunt will be reviewed in the next section.

2.3. Agricultural Residue Biomass Slurries in Pipes

Mohammadabadi [32] was the first to experimentally study the feasibility of pipelining biomass materials in the form of solid-liquid mixtures (slurries). Mohammadabadi designed, fabricated, and instrumented a 50 mm diameter and 25 m long closed-circuit lab-scale pipeline facility in the Large-scale Fluids Lab at the University of Alberta, and successfully pumped wheat straw-water mixtures up to a solid mass content (dry-matter) of 6.5%. Mohammadabadi mainly focused on the change in wheat straw particles' physical properties through exposure to water. For instance, the change in wet-basis moisture content of particles with nominal dimensions (labelled after the size of the classifier sieves openings) of 3.2 mm and 19.2 mm was measured while the particles were being soaked and mechanically mixed for 192 hours. The samples containing small size particles absorbed water faster, the final moisture level (saturation level) of the samples of large size particles was greater (81.2% vs. 81.0%), and mechanical mixing compared to soaking increased the magnitude of absorption (82.4% vs. 81.2% for 19.2 mm particles) as well as the rate of absorption of water into wheat straw particles. In addition, the saturated particle density of wheat straw samples was found to be greater for smaller particles compared to larger ones (1050 kg m^{-3} vs. 1030 kg m^{-3}) and greater after 192 hours of mixing compared to the density obtained after the same amount of soaking time (1060 kg m^{-3} vs. 1050 kg m^{-3} for 3.2 mm particles). The lab-scale closed-circuit pipeline facility created by Mohammadabadi was used later by Luk et al. [31, 33] and Vaezi et al. [16, 17] to experimentally investigate the hydraulics of pipeline transport of agricultural residue biomass slurries.

Luk et al. [31, 33] studied the pressure drop behavior of wheat straw-water mixtures for wheat straw particles of dimensions of 3.2, 6.4, and 19.2 mm, solid mass contents (dry matter) of 1.92, 3.90, and 5.94%, and slurry bulk velocities of 1.5 to 3.0 m s^{-1}. Luk et al. realized that fibre-like wheat straw particles can suppress the flow turbulence at elevated velocities of more concentrated flows and cause the pressure drop to fall below the pressure drop of water alone (the drag-reduction effect).

In order to obtain the true specifications of knife-milled pre-classified wheat straw and corn stover in the Large-scale Fluids Lab., Vaezi et al. [19] used the ImageJ [42] image processing platform and developed a user-coded plugin to obtain the particle dimensions, particle size distribution, size distribution algorithms, shape factors, and other morphological features of wheat straw and corn stover. Large dimensions of 2.0 to 9.0 mm (length), small aspect ratios of 2 to 7, and uunusual characteristics, e.g., wide size distribution and fibrous, pliable, flexible, and asymmetric nature, distinguished agricultural residue biomass fibres from conventional solid particles, e.g., coal, ash, and sand.

Vaezi et al. [16, 17] critically examined the applicability of previously developed correlations for wood chip- and conventional solid particles-water mixtures pressure drop in estimating friction losses while hydraulically transporting wheat straw and corn stover particles. The correlations were found to be inapplicable to the slurries when the slurries of wheat straw and corn stover fibres exhibited unique friction loss behavior, and pressure drop values dropped below that of clear water at elevated velocities, i.e., the drag-reduction effect, as had been previously reported by Luk et al. [33] too. The authors later proved the direct benefit of such drag-reducing ability in reducing pipeline system pumping requirements [17].

Vaezi et al. [16] then studied the change in slurry friction loss and rheological behaviors with the change in agricultural residue biomass particles type (wheat straw and corn stover), particle nominal dimension (<3.2, 3.2, 6.4, and 19.2 mm), slurry solid mass content (1.0 to 8.8% dry-matter - solid volume content of 1.8 to 14.7%), and slurry velocity (0.5 to 5.0 m s^{-1}). A drag reduction of 33% was reported for a 7.6% slurry of <3.2 mm wheat straw particles at 5.0 m s^{-1} (Fig. 1(a)). An increase in slurry solid mass content inversely changed the slurry friction loss compared to conventional solid-liquid systems and decreased the slurry pressure gradient. Large particle size and broad particle size distribution were also found to produce lower friction losses at high flow rates (Fig. 1(b)). Variations in momentum transfer mechanisms, carrier fluid and apparent suspension viscosities, and slurry network strength were the major reasons reported behind such unique behaviors.

Fig. 1

Vaezi et al. [17] later investigated the effect of wheat straw particles on the performance characteristics of an open-impeller centrifugal pump. They studied the change in total head height, efficiency, and power consumption of the pump with the change in solid particle dimension and slurry solid mass content. In clear contrast to the performance of the centrifugal pumps handling slurries of conventional solid particles, the head height produced by the centrifugal pump here increased with an increase in slurry solid mass content for the entire range of flow rates (0.5 to 5.0 m s^{-1}) and particle dimensions (<3.2 to 19.2 mm) (Fig. 2(a)). With regard to the power consumption of the pump, the input power for the pump handling slurries of <3.2 mm particles dropped below the power required by the pump handling pure water only throughout the entire range of flow rates and solid mass contents. In addition, the efficiency of the pump, while centrifugally pumping the slurries of <3.2 mm wheat straw fibres, was 2.0 to 20% higher than the same pump handling pure water only (Fig. 2(b)). The unique performance of the pump while handling wheat straw solid particles was mainly attributed to particle drag-reducing effect, change in slippage, or damping of turbulence.

Fig. 2

3. Empirical Correlations

3.1. Introduction

Reliable correlations are necessary to predict friction loss at the design conditions of piping systems that transport biomass slurries to prevent oversized systems and needlessly high capital and operating costs [8, 43]. However, over fifty years of research have not yet produced a universally applicable correlation for the transport of biomass-water mixtures in pipes. The basic reason is the complex flow behavior of such mixtures which is not yet sufficiently well understood [8]. The carrier liquid could be Newtonian or non-Newtonian (fluid which viscosity or flow behavior changes under stress), the slurry flow could be laminar or turbulent (flow in which the fluid undergoes irregular fluctuations and the speed of the fluid at a point is continuously undergoing changes in both magnitude and direction), and the mixture could be classified as settling or non-settling (no tendency shown by particles in mixture to settle under no-flow conditions) [1]. In addition, there are several modes of particle motions (flow regimes) in hydraulic conveying, depending on how the particles are distributed over the cross section of horizontal pipe (function of particle size, mixture velocity, and mixture concentration). Newitt and Richardson [44] listed those modes as suspended flow, suspended flow with a moving bed, suspended flow with a stationary bed, and saltation with a stationary bed. The conditions at which any of those modes are dominant are illustrated in Fig. 3.

Fig. 3

The present section reviews correlations proposed to predict the mechanical behavior of wood chip-water mixture flows of various modes, as discussed above, in pipes. A deviation of 30% between estimated values of the friction loss of the same mixture using various correlations, and a deviation of 300% between estimated values and experimental measurements were reported in literature, both of which pointed out the need for additional experimental work. The size and density of the wood chips, as well as the density and viscosity of the carrier liquid were among those variables not considered in some of the proposed correlations. However, all the effective variables were included in the more recently developed equations, where a standard deviation of 12% from previously obtained experimental data was reported.

3.2. Correlations

In 1952 Durand and Condolios [46] presented a universal correlation to estimate the friction loss in solid-liquid pipelines (Eq. 1). α and β constants were later empirically determined by Worster [47] and Gibert [48]. The former found constants of 81 and -1.5 for coal-water mixtures, and the latter found constants of 180 and -1.5 for sand- and gravel-water mixtures. Following a study on hydro-transport of spruce and balsam fir wood chips, Elliott and de Montmorency [10, 21] modified the Durand equation and proposed an empirical correlation (Eq. 2) for estimating friction loss in wood chip-water mixtures flowing in pipes. They also recommended a pumping velocity close to 1.2 m s^{-1} where the friction losses were high enough to be technically and economically satisfactory.

$$\frac{i_m - i_w}{i_w . C_v} \cong K \left[\frac{V_m^2}{gD(s-1)}\sqrt{C_D}\right]^{m} \quad (1)$$

$$\frac{i_m - i_w}{i_w . C_v} = 211 \left[\frac{\sqrt{D}}{V_m}\right]^{2.25} \quad (2)$$

Faddick [11] presented the following Durand-type correlation (Eq. 3) for friction loss in wood chip pipelines based on experimental studies. Faddick's results appeared to give predicted friction loss values as much as 30% higher than those of Elliot and de Montmorency [22].

$$\frac{i_m - i_w}{i_w . C_v} = 2.51 \left[\frac{4gD}{V_m^2}\right]^{1.42} \quad (3)$$

Brebner [24] experimentally studied the feasibility of hydro-transporting jack pine and spruce wood chips and measured the friction loss throughout the pipe. With results similar to Elliott's [10, 21], Brebner reported the hydraulic gradients of wood chip-water mixtures in a Durand-type equation as follows:

$$\frac{i_m - i_w}{i_w . C_v} \cong 18 \left[\frac{V_m^2}{gD}\right]^{-1.5} \quad (4)$$

While adopting the Durand equation (Eq. 1) for wood chip results in an equation constant of 6.0, Brebner measured a three-times-larger friction loss with a constant of 18.0. Brebner attributed his findings to the interlocking sliding bed mode of transport. He also successfully tried a pumping velocity as low as 1.5 m s^{-1} in which, since it was the commonly accepted velocity for water alone, he found no advantage going below such velocity.

Wasp et al. [40] introduced a model that is widely used in coal pipeline hydro-transport to classify the particles as either uniformly distributed (homogeneous) or with solid volume fraction gradient across a cross section (heterogeneous or partially stratified). Wasp's model calculates the friction loss per unit pipe length as the sum of losses due to water+suspended fine particles flow (Eq. 5) and water+coarse particles flow (Eq. 1) together with the amount of suspended particles contributing to the former flow (Eq. 6). Following an experimental study on pipeline hydro-transport of wood chips [28], Wasp investigated solid volume content distribution and calculated the solid volume fraction at the top (C_{top}) and middle (C_{mid}) of the pipe. It was found that for every 7 chips at the top, there were 100 chips at the center. This implied that the solid volume content distribution was non-uniform and that the nature of the flow was heterogeneous.

$$i_m = \frac{(0.0032 + 0.221 Re_m^{-0.237})\, V_m^2}{2g} S_m \quad (5)$$

$$\log \frac{C_{top}}{C_{mid}} = -1.8 \left(\frac{w_\infty}{\beta \kappa V_m \sqrt{\frac{f_m}{8}}}\right) \quad (6)$$

Wasp et al. [40] examined the compatibility of the Durand correlation with the published data of Elliott and de Montmorency. While a good agreement was observed for 10-20% solid volume content, a systematic trend for the Durand equation to predict high values for low concentrates (i.e., 5% solid volume content) and low values for high concentrates were found. Zandi and Govatos [49] proposed a criterion to determine the transition in flow regimes from heterogeneous (suspension) to discontinuous sliding bed with saltation and improved the original Durand equation by eliminating the corresponding saltation data. Observing the apparent inconsistency between Elliott and de Montmorency's [10] and Faddick's [11] experimental results, Wasp et al. also attempted to refine the Durand equation by modifying its constants, as proposed by Zandi and Govatos [49]. However, the Zandi and Govatos correlation did not fit the data any better than the old Durand equation, which pointed out the need for additional experimental work.

Faddick [30] simulated the pipeline hydro-transport of wood chips using uniform-sized plastic chips to investigate friction loss parameters. With the data from four sets of experiments using plastic chips and three sets of experiments (by other researchers) using wood chips, Faddick proposed calculating the friction loss in wood chip pipelines using the Darcy-Weisbach equation and evaluated the mixture friction factor using curve-fitting techniques as follows:

$$\log f_m = a_1 C_v \left(\frac{D}{d}\right)^x + a_2 \log(Re_w) + a_3 C_v \left(\frac{D}{d}\right)^y \log(Re_w)^2 \quad (7)$$

where a_1, a_2, a_3, x, and y are empirical coefficients determined experimentally.

Metzner and Reed [50] developed a semi-theoretical correlation to analyze friction loss of laminar non-Newtonian fluids (Eq. 9), and Dodge and Metzner [51] extended their method to include turbulent non-Newtonian fluids (Eq. 10). Gow found Metzner and Reed's method for laminar non-Newtonian flows to be capable of analyzing the friction loss data for wood chip-water mixtures in pseudo-laminar flow (sliding bed) conditions, where *n* and *K* coefficients were obtained from wood chip-water mixture friction loss data as functions of solid volume contents. Gow also indicated that the ratio of friction factors of two various pipe diameters equals the reciprocal ratio of the pipe diameters to the *n* power (Eq. 11).

$$Re_m = \frac{D^n V_m^{2-n} \rho_m}{8^{n-1} K} \quad (8)$$

$$f_L = \frac{16}{Re_{MR}} \quad (9)$$

$$\frac{1}{\sqrt{f_T}} = \frac{4}{n^{0.75}} \log\left(Re_{MR}\, f_T^{\,1-\frac{n}{2}}\right) - \frac{0.4}{n^{1.2}} \quad (10)$$

$$\frac{f_{L,1}}{f_{L,2}} = \left(\frac{D_2}{D_1}\right)^{\square} \quad (11)$$

However, the correlation for turbulent non-Newtonian flows proposed by Dodge and Metzner [51] was not applicable for wood chip-water mixtures in pseudo-turbulent (saltation flow) regions. Because of the similarity between friction loss curves for wood chip-water mixtures in pseudo-turbulent regions and clear water lines defined by Prandtl's universal law of friction for turbulent pipe flow (Eq. 12), Gow [12] proposed a new correlation (Eq. 14) where, with friction loss experimental data, a plot of $\frac{1}{\sqrt{f_m}}$ versus $\log(Re_m\sqrt{f_m})$ gives the constant value *A* and the quantity $(E - A\log\varphi)$ as the slope and the ordinate intercept, respectively. Assuming Eq. 13 to be valid, Gow found the coefficients *A* and *logφ* to be 4.0 and 0.0 for a 0% solid volume content and *E* to be -4.0 for all the mixture solid volume contents. Gow also observed that the wood chip-water mixture viscosity, as defined by Eq. 13, increased with increasing mixture solid volume contents and became larger for larger chip sizes. Gow found such viscosity variation to be the result of increased particle-wall interaction due to increased solid volume content and decreased turbulent intensity due to increased chip size.

$$\frac{1}{\sqrt{f_w}} = 4 \log\left(Re_w \sqrt{f_w}\right) - 0.4 \quad (12)$$

$$\frac{\mu_m}{\mu_0} = \square(\square_{\square}, \square_{\square}, \square, \square_{\square}, \square_{50}) \quad (13)$$

$$\frac{1}{\sqrt{\square_{\square}}} = \square\ \square\square\square\ (\square\square_{\square}\sqrt{\square_{\square}}) + \square - \square\square\square\square\square \quad (14)$$

Hunt [22] studied the hydro-transport of wood chip-water mixtures and examined the applicability of the extrapolation approach to friction loss correlations proposed by Gow [12] and Faddick [30]. Hunt found the failings on previously developed correlations to be: (1) the difficulty in calculating the wood chip density and drag coefficients for Eq. 1 by Durand; (2) the lack of inclusion of the effect of particle-to-pipe size ratio for Eq. 2 by Elliott and de Montmorency and Eq. 3 by Faddick; (3) the non-consideration of the viscosity of the carrier liquid (water) for Eqs. 1, 2, and 3; (4) the lack of convergence to the clear water friction factor for a mixture solid volume content of 0% for Eq. 7 by Faddick; and (5) the inconsistency with values reported by Elliott and de Montmorency in 200 mm pipes [10] for Eq. 9 and by Gow for Eq. 14. To correct these deficiencies, Hunt proposed a correlation (Eq. 16) to predict the wood chip-water mixture friction loss in terms of an excess friction factor ($f_m f_w^{-1}$ -1) as a function of four dimensionless parameters (Eq. 15). In the selection of a mathematical model for fitting the data into a single equation including all four dimensionless groups of Eq. 15, Hunt modified the mixture solid volume content (C_v) and particle-to-pipe size ratio (P) to satisfy two boundary conditions; the mixture friction factor should be identical with that of clear water when the mixture solid volume content equals zero, and the mixture friction factor for a given mixture solid volume content should increase with an increase in the particle-to-pipe size ratio. Hunt's expression for a wood chip-water mixture friction factor brings about a standard deviation of about 12% from previously reported data [10, 12, 29, 30] on pipes of 75 mm, 100 mm, 150 mm, 200 mm, and 300 mm diameter.

$$\frac{\square_{\square}}{\square_{\square}} - 1 = \square[(\frac{\square_{\square}^{3}}{\square\square}), (\frac{\square^{1.5}\square^{0.5}}{\square}), \square_{\square}, (\frac{\square_{50}}{\square})] \quad (15)$$

$$\frac{\square_\square}{\square_\square} - 1 = 197\left(\frac{\square^{0.97}\,\square^{1.312}\,\square^{0.342}}{\square_\square^{2.964}}\right)\left(\frac{\square_\square}{1-\square_\square}\right)^{0.838+0.930\,\square\square(1-\square)} \quad (16)$$

Vaezi et al. [16, 17, 19] conducted a series of experiments on the morphological features of wheat straw and corn stover agricultural residue (non-wood) biomass, as well as longitudinal pressure gradients of residue-water mixtures in pipes and the change in the performance of the centrifugal slurry pumps handling such mixtures. Later, Vaezi et al. [18] used EViews 7.1 [52] econometric software to analyze the pressure gradients measured through the experimental course of the pipeline transport of wheat straw- and corn stover-water mixtures. Introducing a fourth-order polynomial equation and using the nonlinear least square (NLS) regression analysis model, they developed an empirical model (Eq. 17) capable of predicting, with an uncertainty less than 10%, the dependent variable of longitudinal pressure gradient (kPa m^{-1}) as a function of the independent variables of slurry bulk velocity (m s^{-1}), slurry solid mass content (dry matter, %), and solid particle size representative (particle shape factor, dimensionless). The shape factor was defined to take into account the physical properties and shape characteristics of the particles (Eqs. 18 and 19) and to extend the specific results obtained here to other fibrous non-wood particles. Vaezi et al. also adopted three scale-up approaches to incorporate the pipeline specification (i.e., pipeline diameter) in the correlation where it was found by increasing the diameter of the pipe, the pressure gradient will be modified proportional to $D^{-1.2}$.

$$\frac{\Delta\square}{\square} = (1.22\square - 1.97\square^2 + 0.16\square_\square^2 - 0.001\square_\square^2\square_\square^2 + 0.64\square^3 + 0.0006\square_\square^3)\left(\frac{\square}{0.05}\right)^{-1.2} \quad (17)$$

$$\square = \frac{\square_\square}{\square_\square \times \sum_{\square=1}^{\square}(\square_{\square\square,\square\square\square\square\square} \times \square)}\ \square = \frac{\square_\square}{\square_\square \times \sum_{\square=1}^{\square}(\square_{\square\square,\square} \times \square_{\square,\square})} \quad (18)$$

$$\square\square\square\square\square\ \square\square\square\square\square\square\square = \square \times \sqrt{\square\square \frac{\square_{\square\square,\square\square\square\square\square}}{\square_{\square\square}}}\text{Shape factor } (S) = \square \times \sqrt{\frac{\square_{\square\square}}{\square_{\square\square}}} \qquad (19)$$

4. Economic Assessments

4.1. Introduction

Based on experimental measurements and empirical correlations reported in the literature, a few researchers studied the economic feasibility of pipelining wood chip-water mixtures to processing plants. The concept of economy of scale was found to be highly applicable to pipeline systems, the water required at the pipeline inlet was reported to be not exceptionally large (in relation to the amount of resources available on most timber limits), and a 25% variation in the total cost of a pipeline system was obtained by using various pressure drop correlations. It was shown that the power required and, accordingly, the operating costs of the pipeline system would decrease and the capital costs of the pipeline system would increase with an increase in solid volume content, decrease in mixture velocity, and increase in pipeline length. Furthermore, capital charges were reported to account for more than 70% of the total transportation cost.

4.2. Techno-economic Studies

Following an empirical study on pipeline hydro-transport of pulpwood chips, Elliot and de Montmorency [10, 21] studied the economic feasibility of wood chip transport via a hypothetical system of pipelines leading from a landing to the mill (Fig. 4). The forest field included a productive area of 2300 km^2 with an annual cut of 900 dam^3. The aluminum pipeline was composed of surface-laid branch pipelines converging into a buried feeder line that discharged into a buried main line. Elliot and de Montmorency argued that the amount of water required, e.g., 4000 $dam^3\ y^{-1}$ to transport 1500 $dam^3\ y^{-1}$ of wood chips in a 40% solid volume content mixture, was not exceptionally large in terms of the amount of resources available on most timber limits. Further, they presented the power loss per kilometer distance for 150 mm, 200 mm, and 250 mm diameter pipes carrying wood chips at mixture solid volume contents of 20%, 30%, and 40%. It was shown that power and operating costs could be lowered by increasing the mixture solid volume content and decreasing the pumping velocity, which would also increase capital investments. The direct economic benefits named by researchers included low unit transportation costs for an annual capacity over 700 dam^3, a minor increase in transportation costs over a period of 20 years due to low labor requirements, low depreciation compared to new road or rail construction, and a drastic reduction in mill, forest, and in-transit inventories.

Fig. 4

Using only those friction losses found experimentally, Brebner [24] calculated the cost of transport of a 35% solid volume content wood chip-water mixture in a 200 mm diameter pipeline at 2.0 m s^{-1} pumping velocity and 55% pump/motor efficiency to be 0.095 \$ $t^{-1}km^{-1}$. Brebner did not measure wear, corrosion, or erosion in the pipe (all of which could increase both the operating and the capital costs).

The Georgian Research Institute of Forest Industry fabricated a laboratory-scale pipeline facility to investigate the technology and the economy of pipeline transport of wood chips-water mixtures for pulp and paper production purposes [25]. The research institute derived the cost estimates based on the guide on canalization and water system construction (Leningrad water canal report) while taking into account the cost of steel pipes, installations, and digging 2 m trenches in dry soil. Amortization costs were considered to be 3.5%, including all repairs and complete replacement. The annual maintenance cost was estimated at 6000 \$ km^{-1} and the transportation cost was estimated at 0.08 \$ m^{-3} km^{-1}. With this means of transport, the cost of production of pulpwood was calculated to reduce by 80% per cubic meter of solid wood chips.

Wasp et al. [28], while reviewing wood chip pipelining, discussed the related economics. Fig. 5(a) presents the investment cost and Fig. 5(b) shows the capital costs (including carbon steel pipe, external coating, installation costs, positive displacement pump stations and related facilities, communication system, water supply system, chip injection facilities, terminal dewatering facilities, and indirect costs including a contingency allowance, interest during construction, working capital, and engineering management) and the operating costs (including electrical power costs for driving the pumps and mixing, costs of operating personnel for the pipeline system, an allowance for chemical corrosion inhibitors, supplies and maintenance for the pipeline and pump stations, administration costs, and a contingency allowance) of such pipelines based on a 100 km long pipeline capable of hydro-transporting various amounts of so-called green (35% moisture content) wood chips at 20% solid volume content. Wasp also found the sensitivity to change in length to be quite low, e.g., a 50% reduction in length causes a 7% increase in total unit transportation costs. In addition to showing the concept of economy of scale, which is found to be highly applicable to pipeline systems, Fig. 5 shows that capital charges account for more than 70% of the total transportation cost, i.e., once the pipeline is constructed, 70% of the transportation costs are not subject to increase. This is a distinct advantage of pipeline hydro-transport over nearly every other mode of transport. To achieve these results, Wasp used Elliot and de Montmorency's [10] friction loss data. Using Faddick's [11] data increased the total and capital costs by 25%.

Fig. 5

Hunt [53, 54] conducted an analysis to determine the conditions under which a pipeline system might be economically competitive with other methods of transporting wood chips to processing plants. The economic model to determine the cost of transporting one tonne of wood chips for one kilometer by a given transportation system included the capital investment, operating expenses, and associated overhead charges. Hunt subdivided the costs into seven groups, each depending on one or more of the 23 variables selected to formulate the algebraic expressions that relate the hydraulic properties of the pipeline and physical properties of the wood chips to the economics of the system. Using Brebner's friction loss equation [24], the total cost per one tonne of wood chips per unit distance can be found with Eqs. 23 to 30 for each of the seven cost groups previously mentioned.

$$\square_{\square} = \square_{\square}[(\square\square + 1)\square_{\square\square\square} - 1] + 1 \quad (20)$$

$$\square = \frac{1}{216\square\square^{5}}\frac{\square}{\square_{\square}\square_{\square\square\square}} \quad (21)$$

$$\square_{\square} = 31{,}680(0.547\square^{-1.42} + 1)\square_{\square}\square + \frac{\square_{\square}}{\square} \quad (22)$$

$$\square_{\square} = \sum_{\square=1}^{7} \square_{\square} \quad (23)$$

$$\square_{1} = 0.000753\,\frac{\square_{1}}{\square\,\square_{\square\square\square}}\frac{\square_{\square}\,\square_{\square}}{\square_{\square}} \quad (24)$$

$$\square_{2} = \frac{\square_{2}\,\square}{365\,\square}(\square\square\square) \quad (25)$$

$$\square_{3} = 0.000000115\,\frac{\square_{3}}{\square\,\square_{\square\square\square}}\frac{\square_{\square}\,\square_{\square}}{\square_{\square}}(\square\square\square) \quad (26)$$

$$\square_{4} = \frac{\square_{4} + \square_{5}}{365\,\square}(\square\square\square) \quad (27)$$

$$\square_5 = \frac{\square_6}{365\ \square\ \square} \tag{28}$$

$$\square_6 = \frac{1}{365\ \square}\ \square_7\ \frac{\square_{\square}}{\square_{\square\square}} + \square_8 \tag{29}$$

$$\square_7 = 0.000240\ \frac{1-\square_{\square}}{\square_{\square}}\frac{\square_9}{\square_{\square\square\square}\ \square} \tag{30}$$

Table 2

Developing a computer program and using the cost data listed in Table 2, Hunt obtained the cost per tonne per unit distance for transporting various amounts of wood chips per day (500 t, 1000 t, and 2000 t). An investigation of the effect of mixture solid volume content, pipe diameter, pipe length, and wood chip transport capacity per day on the total cost per tonne per unit distance (e.g., Fig. 6(a)) showed a 10% reduction in the unit cost when the same volume was transported in a line twice as long and a 30% reduction in the unit cost when the volume was double for a given distance. 20-22% mixture solid volume content was found to be the maximum working solid volume content for wood chip pipelines. Hunt also indicated that the optimum solid volume content to transport 500 t d^{-1} of wood chips over 160 km was approximately 21% for 200 mm diameter, 14% for 250 mm diameter, and 9% for 350 mm diameter pipelines.

Hunt [55] collected data for the cost of transportation by truck and rail from 43 pulp mills in the Great Lake states, as well as northwest, northeast, and southern regions in U.S., and compared the cost per tonne per unit distance for pipeline hydro-transport of wood chips with that for truck and rail haul (Fig. 6(b)). It was found that hydro-transport of wood chips in quantities greater than 1000 t d^{-1} could compete economically with the rates for truck haul and northern railroad haul for distances up to 88 km. However, if the cost of the construction of highways and railroads was also included in Hunt's transportation cost database, the cost of pipeline hydro-transport would be much more favorable.

Fig. 6

Kumar et al. [13-15] conducted a series of techno-economic analyses on pipeline hydro-transport of wood chips and pipeline hydro-transport and simultaneous saccharification of corn stover. Drawing on the works of Wasp et al. [28] on pipelining wood chips and Liu et al. [56] on pipelining compressed coal cylinders, Kumar et al. [15] developed pipeline cost estimates for transporting wood chip-water mixtures; these estimates are shown on Table 3 and Fig. 7(a). Comparing the cost of truck delivery of wood chips with the cost of pipeline transport of a wood chip-water mixture with solid volume content of 30% over an arbitrary pipeline length of 160 km, the marginal cost of pipeline hydro-transport was found to be higher than truck delivery cost at capacities <0.5 M t y^{-1} dry wood chips for a pipeline without the return line for the carrier liquid (one-way). The corresponding minimum capacity for a pipeline with the return line for the carrier liquid (two-way) was 1.25 M t y^{-1} dry wood chips. It was shown that the minimum length of the pipeline to recover the fixed costs of a pipeline with a capacity of 2.0 M t y^{-1} dry wood chips was 75 km for a one-way pipeline and 470 km for a two-way pipeline (in addition to the initial 35 km truck haul to the pipeline inlet). In addition, the authors investigated the drop in the lower heating value (LHV) of biomass because of the take-up of the carrier liquid and discussed the limited application of pipeline hydro-transport of biomass to supply aqueous-based processes only, e.g., bio-ethanol production or supercritical water gasification.

Table 3

Kumar et al. [15] also investigated the pipeline hydro-transport of corn stover and found the one-way pipeline at a scale of 1.0 to 2.0 M t y^{-1} dry corn stover and mixture solid volume content of above 15% to cost less than truck delivery (Fig. 7). To estimate the corn stover-water mixture friction factor in pipes, Kumar et al. used Hunt's correlation [22], which was originally proposed for wood chip-water mixtures in pipes. However, they examined the sensitivity to friction factor parameter and found that a variation of -50% to +100% in friction factor results in a -16% to +31% change in the distance variable cost of pipeline hydro-transport of corn stover, a sensitivity that did not invalidate the conclusion of the study.

Fig. 7

Ellis et al. [61] considered the possibility of partial processing-in-transit through solid-liquid mixture pipelines. Nardi [34] suggested a similar technique for wood chips to inject the chemicals into a heated section near the receiving facility. Kumar et al. [15] examined the simultaneous saccharification and transport (SST) on a corn stover hydro-transport pipeline. It was found that, since the current cellulase enzyme (that converts starch into sugar) causes an acidic environment in the pipe, the SST requires a prohibitively expensive stainless steel pipeline that makes it technically and economically inapplicable. Furthermore, residence time and mixture temperature are critical factors, as National Renewable Energy Laboratory (NREL) suggests a contact time of 35 hr at a saccharification temperature of 65°C [62]. The fuel cost for heating a corn stover-water mixture by 40°C using natural gas at 5 $ GJ^{-1} was estimated to be more than 0.069 $ L^{-1} of produced ethanol. Insulation might also be required, specifically for smaller capacity pipelines buried in the soil. Furthermore, it was found that insulating a 100 mm diameter pipeline carrying 1.5 M t y^{-1} dry corn stover with 25 mm of foam would cause an approximately 15% increase in the installed cost of a corn stover-water mixture pipeline and a 10% increase in the distance variable cost.

5. Conclusion

Using pipeline hydro-transport to replace traditional modes of delivery i.e., road, rail, and river, is a major step towards building large-scale bio-based facilities. This paper reviewed the literature published on pipeline hydro-transport of wood chips and agricultural residue biomass for pulp and paper production, as well as for fuel and energy generation. The technical challenges and economic issues were reviewed, and correlations to predict biomass-water mixture mechanical behavior were introduced.

None of the studies conducted either experimentally or theoretically considered wear, corrosion, or erosion in a pipeline, all of which could impact the mechanical specifications (e.g., friction loss) and economic features (e.g., capital cost) of the pipeline and which should be measured/calculated in future studies. As described in this paper, pipeline hydro-transport of wheat straw and corn stover biomass has been experimentally studied on a 50 mm diameter and 25 m long (laboratory-scale) horizontal pipeline facility. The scaling up of such a pipeline must be studied to understand how the change in pipeline diameter and orientation would change the slurry mechanical behavior. More research needs to be conducted to develop empirical correlations to estimate corresponding slurry friction loss. Such correlations could be used to study the economy of agricultural residue pipelines, as previous studies on this field used friction loss correlations originally proposed for wood chip-water mixtures instead. Water mixtures of other sorts of biomass materials could be also investigated to understand how biomass physical specifications would change slurry mechanical behavior. Chemical processing-in-transit through pipeline hydro-transport of biomass materials is another interesting issue that, although its economic viabilities have been analyzed, needs its mechanical and chemical feasibility to be experimentally investigated.

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References

[1] Abulnaga B. Slurry systems handbook. New York, NY, USA: McGraw-Hill; 2002.

[2] Bain AJ, Bonnington ST. The hydraulic transport of solids by pipeline. New York, NY, US: Pergamon Press; 1970.

[3] Weston MD, Worthen L. Chevron phosphate slurry pipeline commissioning and start-up. 12th International conference on slurry technology; March 31 – April 3; Washington, DC, USA; 1987.

[4] How pipelines work? Paris (France): TRAPIL Petrolum pipeline transport company. [Cited April 2013] Available from http://www.trapil.fr/uk/comcamarche4.asp.

[5] Thiesmeyer LR. Hydraulic transport of wood chips by pipeline. In: United Nation/FAO. Conference on pulp and paper developement in Africa and the near east; Cairo, Egypt; 1965. p. 865-876.

[6] Duffy GG. Measurement, mechanisms, and models: some important insights into the mechanisms of flow of fibre suspensions. Trans Annu Nordic Rheol Soc 2006; 14: 19-31.

[7] Lee PFW, Duffy GG. Analysis of drag reducing regime of pulp suspension flow. Tappi 1976 (a); 59(8): 119-22.

[8] Moller K. Correlation of pipe friction data for paper pulp suspensions. Ind Eng Chem Proc Des Dev 1976; 15(1): 16-19.

[9] Paul T, Duffy G, Chen D. New insights into the flow of pulp suspensions. Tappi 2001; 1(1); 74-80.

[10] Elliott DR, de Montmorency WH. The transportation of pulpwood chips in pipelines. Montreal: Pulp and Paper Institute of Canada (PAPRICAN); August 1963. Report No.: 144.

[11] Faddick RR. The aqueous transport of pulpwood chips in a four inch aluminum pipe [dissertation]. Kingston (ON): Queen's University; 1963.

[12] Gow JL. Hydraulic transport of woodchips in pipelines [dissertation]. Bozeman (Mt): Montana State University; 1971.

[13] Kumar A, Cameron JB, Flynn PC. Pipeline transport of biomass. Appl Biochem Biotech 2004; 113(1): 27-39.

[14] Kumar A, Cameron JB, Flynn PC. Large-scale ethanol fermentation through pipeline delivery of biomass. Appl Biochem Biotech 2005; 121(1): 47-58.

[15] Kumar A, Cameron JB, Flynn PC. Pipeline transport and simultaneous saccharification of corn stover. Biores Tech 2005; 96(7): 819-29.

[16] Vaezi M, Katta AK, Kumar A. Investigation into the mechanisms of pipeline transport of slurries of wheat straw and corn stover to supply a bio-refinery. Biosystems Eng 2014; 118(1): 52-67.

[17] Vaezi M, Kumar A. The flow of wheat straw suspensions in an open impeller centrifugal pump. Biomass and Bioenergy 2014 October; 69: 106-23.

[18] Vaezi M, Kumar A. Development of correlations for the flow of agricultural residues as slurries in pipes for Bio-refining. Biosystems Eng 2014 August; 127: 144-58.

[19] Vaezi M, Pandey V, Kumar A, Bhattacharyya S. Lignocellulosic biomass particle shape and size distribution analysis using digital image processing for pipeline hydro-transportation. Biosystems Eng 2013; 114(2): 97-112.

[20] Vaezi M, Nimana B, Kumar A. Is the pipeline hydro-transport of wheat straw and corn stover to a biorefinery realistic? Biofuels Bioprod Bioref 2015; XX: XX.

[21] Elliott DR. The transportation of pulpwood chips in pipelines. Pulp Paper Mag Can 1960 May; 61: 170-75.

[22] Hunt WA. Friction factors for mixtures of wood chips and water flowing in pipelines. 4th International Hydrotransport Conference. Banff, AB, Canada; 1976. p. 1-18.

[23] O'donnell JP. Diversification of owners is common in products pipeline. Oil Gas J 1964; 62: 88-100.

[24] Brebner A. On pumping of wood chips through 4 inch aluminum pipeline. Can J Chem Eng 1964; 42(3): 139-42.

[25] Gulisashvili BG, Nodaraya VL, Korobov VV. Transport of wood chips by water in pipeline. Woodlands Research Index 1964; 150: 5-7.

[26] Hewlett Packard Co. Dymec system speeds wood chip pipeline test. Measure Mag 1965 February: 6-7.

[27] Elliott DR. Chiplines-closer than we think. Pulp Paper Mag 1964 August; 363: 27-29.

[28] Wasp EJ, Aude TC, Thompson TL, Bailey CD. Economics of chip pipelining. Tappi 1967; 50(7): 313-18.

[29] Soucy A. Data supplied to R.R. Faddick by Laval University. Quebec City, QC; 1968.

[30] Faddick RR. Hydraulic transportation of solids in pipelines [dissertation]. Bozeman (Mt): Montana State University; 1970.

[31] Luk J. Pipeline transport of wheat straw slurry [dissertation]. Edmonton (AB): University of Alberta; 2010.

[32] Mohamadabadi HS. Characterization and pipelining of biomass slurries [dissertation]. Edmonton (AB): University of Alberta; 2009.

[33] Luk J, Mohammadabadi HS, Kumar A. Pipeline transport of biomass: Experimental development of wheat straw slurry pressure loss gradients. Biomass and Bioenergy 2014 May; 64: 329-36.

[34] Nardi J. Pumping solids through a pipeline. Chem Eng 1959; 66(15): 26-33.

[35] Coffey GR, Partridge VA. Coal slurry pipelines: the ETSI project. The Right of Way J 1982 August: 11-16

[36] de Souza, JCM, Braganca ACCR, da Cruz Rodrigues CA, Lima ELG. The Samarco pipeline - 26 years of operation. 16th International Hydrotransport Conference; Santiago, Chile; 2004. p. 659-73.

[37] Winter CH, Sillers R, Glowach AM. High temperature insulated coating aids construction of Alberta bitumen pipeline. Oil Gas J 2003 January; 101: 56-58.

[38] Billington DP, Jackson DC, Melosi MV. The history of large federal dams: planning, design, and construction. Denver, CO, US: U.S. Department of the Interior, Bureau of Reclamation; 2005.

[39] Parham CP. The golden dream: a history of the St. Lawrence seaway. Michigan Hist Rev 2011; 37(2): 124-25.

[40] Wasp EJ, Regan TJ, Withers J, Cook PAC, Clancey JT. Crosscountry coal pipeline hydraulics. Pipeline News 1963; 35(7): 20-28.

[41] Schmidt RE. An investigation of the effects of pressure and time on the specific gravity, moisture content, and volume of wood chips in a water slurry [dissertation]. Montana (Mt): Montana State University; 1965.

[42] Rasband WS. ImageJ. Research Services Branch, U.S. National Institutes of Health, Bethesda, Maryland; 2008.

[43] Duffy GG. A review and evaluation of design methods for calculating friction loss in stock piping systems. Tappi 1976; 59(8): 124-27.

[44] Newitt DM, Richardson JF. Hydraulic Conveying of Solids. Nature 1955; 175: 800-01.

[45] Brebner A. An introduction to aqueous hydraulic conveyence of solids in pipelines. Queen's University, Kingston, Ontario: The National Research Council of Canada and The Ontario Mining Association; 1962. Report No. 21

[46] Durand R, Condolios G. The hydraulic trasnport of coal and solid materials in pipes. Conference on hydraulic transport of coal; London; 1952. p. 39-55.

[47] Worster RC. Hydraulic transport of solids. Conference on hydraulic transport of coal; London; 1952.

[48] Gibert R. Hydraulic transport and discharge of mixtures in pipes. Annals of Roads and Bridges; 1960. Report No. 12-17.

[49] Zandi I, Govatos G. Hetrogeneous flow of solids in pipelines. ASCE Hydraul Div J 1967 May; 93: 145-59.

[50] Metzner AB, Reed JC. Flow of non-Newtonian fluids - correlation of the laminar, transition, and turbulent flow regions. Aiche J 1955; 1(4): 434-40.

[51] Dodge DW, Metzner AB. Turbulent flow of non-Newtonian systems. Aiche Journal 1959; 5(2): 189-204.

[52] Quantitative Micro Software (QMS), EViews 7.1. IHS Global Inc., Irvine, CA, USA; 2010.

[53] Hunt WA. Economic analysis of wood chip pipeline. Forest Prod 1967; 17(9): 68-74.

[54] Hunt WA. Continuous flow transport of low value forst products by hydraulic pipeline. Bozman (Mt): Intermountain Forest and Range Experiment Station; 1962

[55] Scheer AC. Survey on wood chips transportation charges. Bozman (Mt): Intermountain Forest and Range Experiment Station; 1962.

[56] Liu H, Noble J, Zuniga R, Wu J. Economic analysis of coal log pipeline transportation of coal. Columbia, Missouri: Capsule Pipeline Research Center (CPRC), University of Missouri; 1995. Report No. 95-1.

[57] Marrison CI, Larson ED. Cost versus scale for advanced plantation-based biomass energy systems in the US and Brazil. 2nd Biomass Conference of the Americas: Energy, Environment, Agriculture, and Industry; Portland, OR; 1995. p. 1272-90.

[58] Jenkins BM, Dhaliwal RB, Summers MD, Bernheim LG, Lee H, Huisman W, et al. Equipment performance, costs, and constraints in the commercial harvesting of rice straw for industrial applications. American Society of Agricultural Engineers (ASAE) Conference. Milwaukee, WI, US: 2000.

[59] Kumar A, Cameron JB, Flynn PC. Biomass power cost and optimum plant size in western Canada. Biomass & Bioenergy 2003; 24(6): 445-64.

[60] Glassner D, Hettenhaus J, Schechinger T. Corn stover collection project. Bioenergy Conference. Madison, WI, USA; 1998, p. 1100-10.

[61] Ellis HS, Redberger PJ, Bolt LH. Slurries: basic principles and power requirements. Indust Eng Chem J 1963; 55(8): 18-26.

[62] Aden A, Ruth M, Ibsen K, Jechura J, Neeves K, Sheehan J, et al. Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover. Golden, Colorado: National Renewable Energy Laboratory (NREL); 2002. Report No. NREL/TP-510-32438.

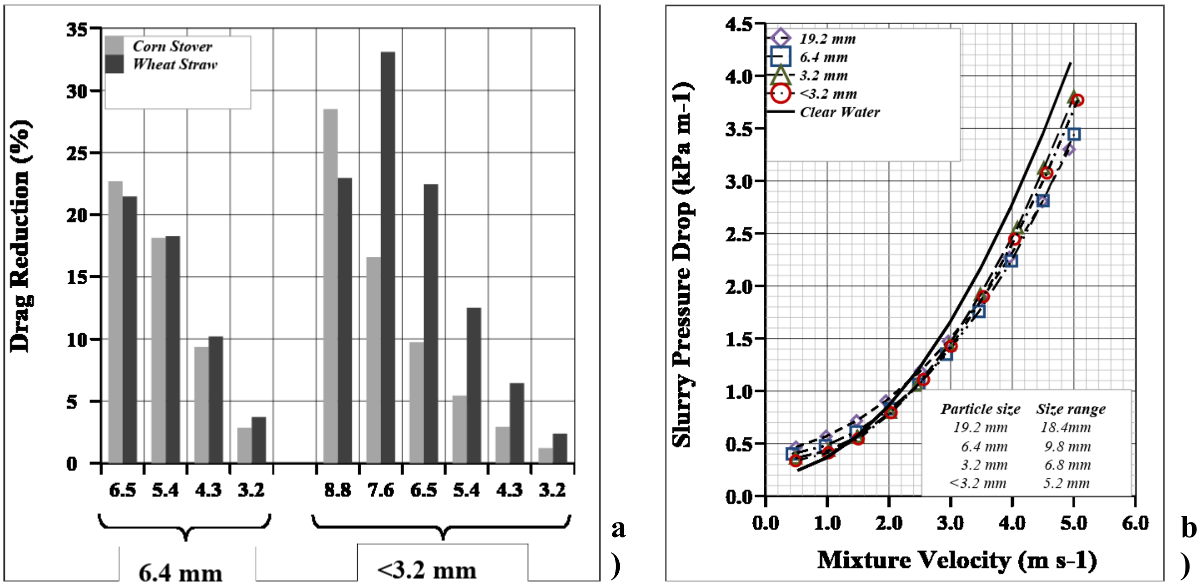

Fig. 1: a) Drag reduction as a function of slurry solid mass content (data not available for 19.2 mm corn stover particles), b) Pressure drop vs. pumping velocity for 5.4% slurries of various size wheat straw particles [16], *Figures reproduced with the permission of Elsevier Publication (license number: 3413821384248)*

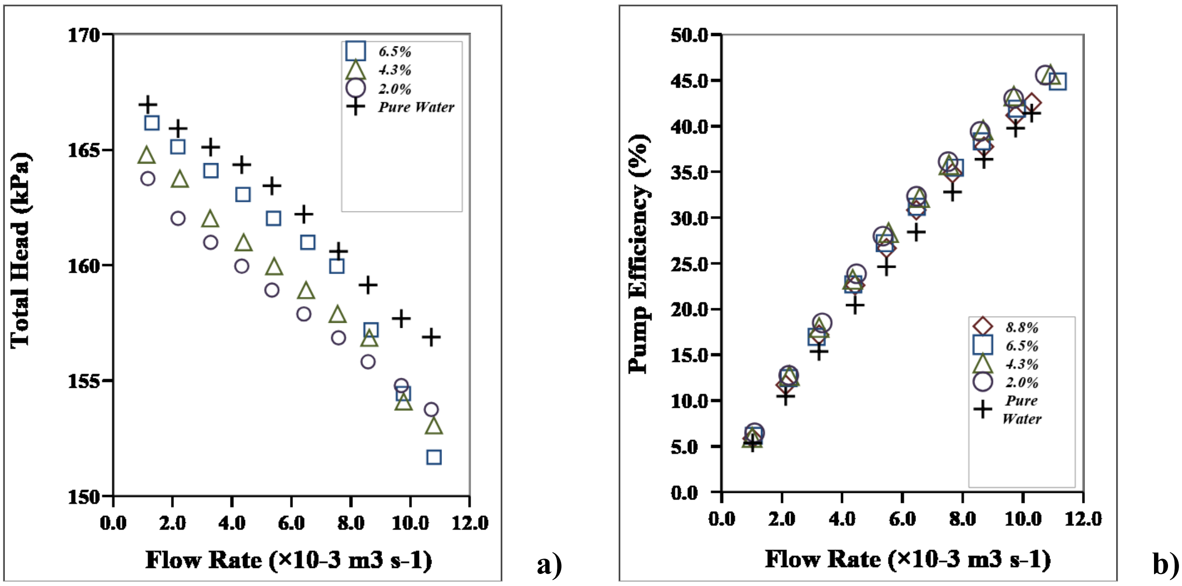

Fig. 2: Centrifugal slurry pump performance characteristics (pump head and efficiency) over a range of flow rates (0.5 to 5.0 m s^{-1}) and dry matter solid mass contents (2.0 to 8.8%) at 185 rad s^{-1} (1765 rpm). a) characteristics of 6.4 mm wheat straw particle slurries; b) characteristics of <3.2 mm wheat straw particle slurries [17] *Figures reproduced with the permission of Elsevier Publication (license number: 3587221437445)*

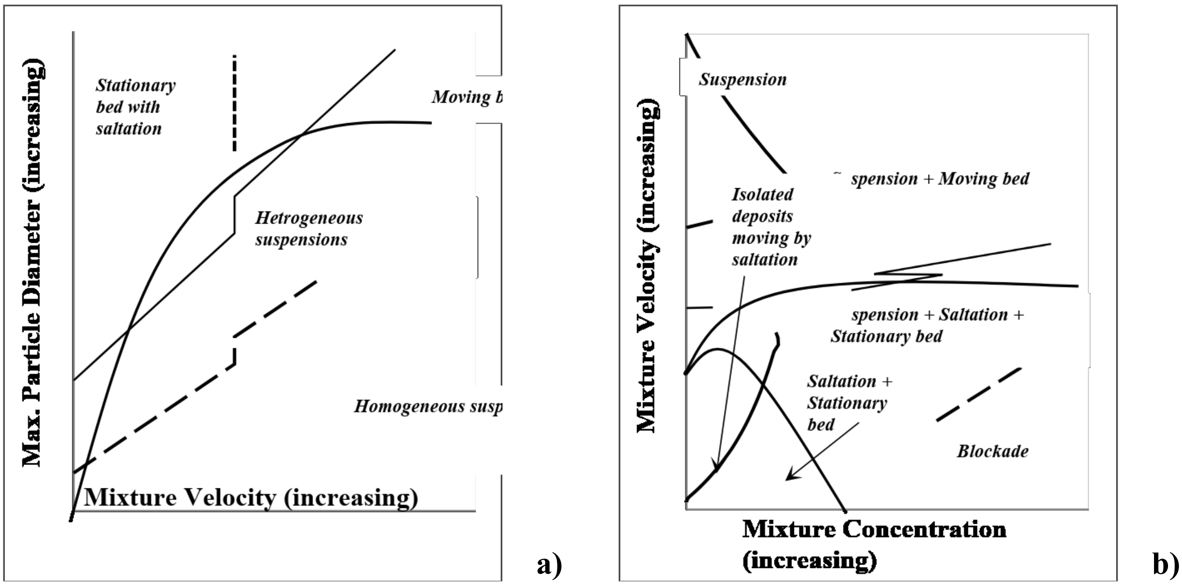

Fig. 3: Various modes of mixture flow in pipes at a) constant mixture concentration, pipe diameter, and particle density, b) constant pipe diameter, particle size, and particle density [45]

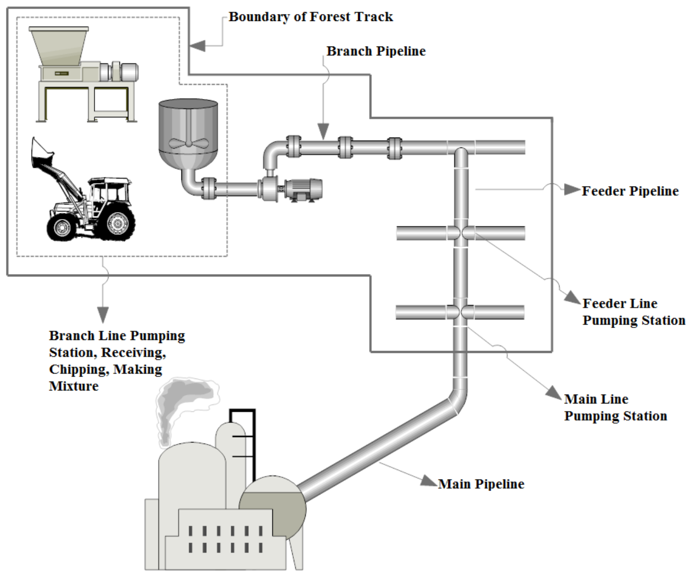

Fig. 4: Layout of the proposed system by Elliot and de Montmorency [10, 21] for the pipeline hydro-transport of wood chips

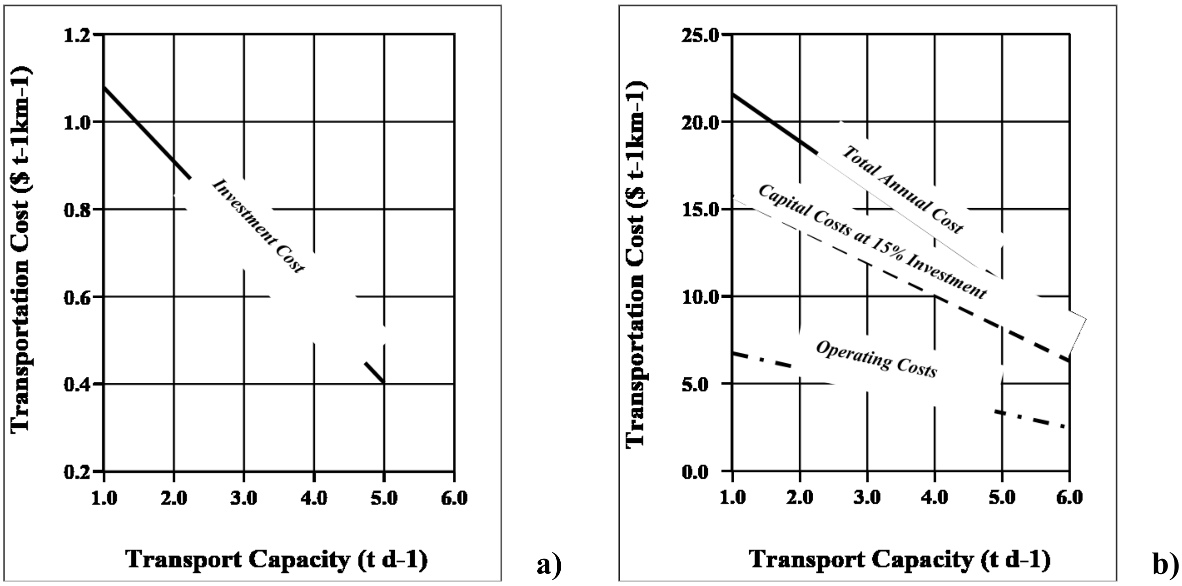

Fig. 5: Wood chip pipeline capital and operating costs vs. pipeline capacity for green chips at 35% moisture content, 20% wood chip-water mixture solid volume content, and 310 operation days per year (operating factor 85%) [28], *Figures reproduced with the permission of Technical Association of the Pulp and Paper Industry (TAPPI) (license number: 3414870205753)*

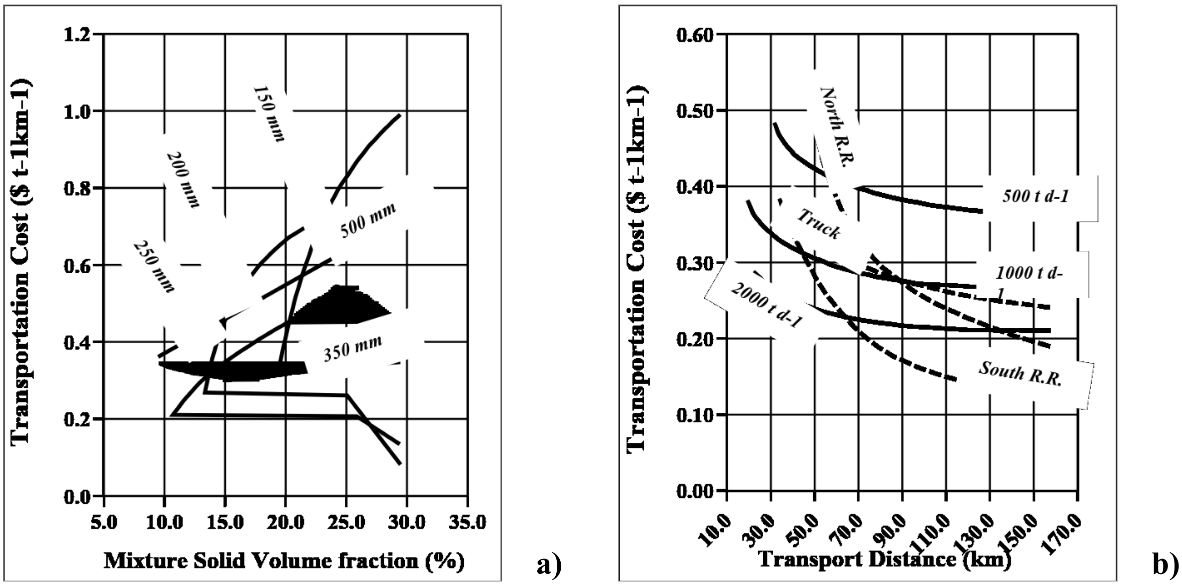

Fig. 6: a) The cost of pipeline hydro-transport as a function of pipeline diameter and mixture solid mass content for capacities of 1000 t d^{-1} over 160 km, b) Comparative transportation costs (both the graphs are based on 365 operation days per year) [53], *Figures reproduced with the permission of Forest Products Research Society (license number: 3413841423702)*

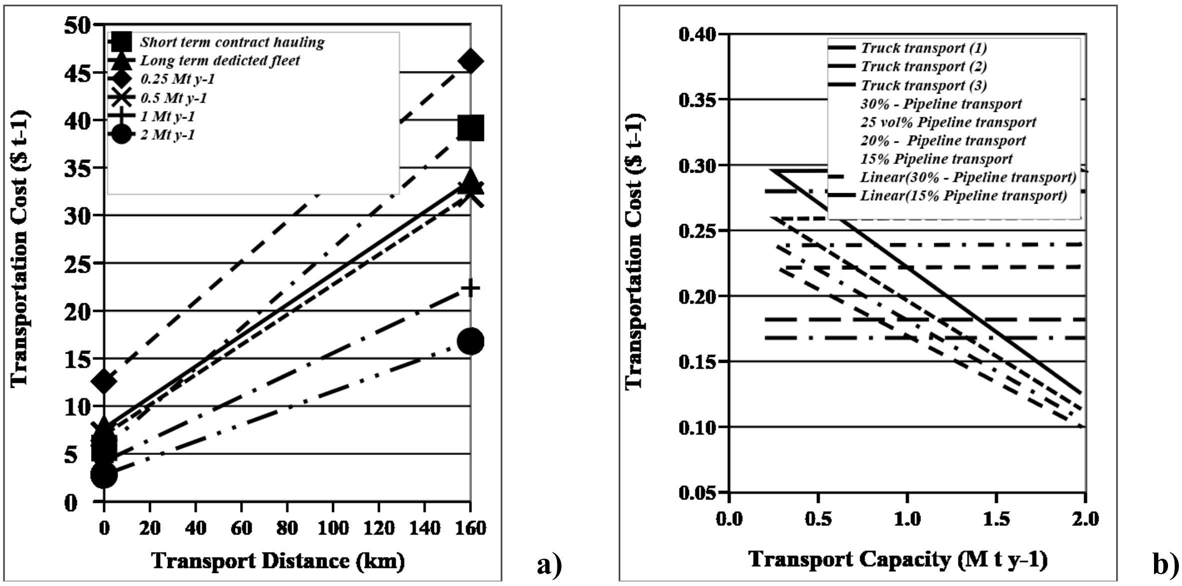

Fig. 7: a) Truck and pipeline hydro-transport costs of wood chips without the return line for the carrier liquid [13], b) Distance variable cost of truck and pipeline hydro-transport of corn stover at different solid volume contents without the return line for the carrier liquid [15], truck transport (1): study by Marrison and Larson [57], truck transport (2): study by Jenkins et al. [58] and Kumar et al. [59], truck transport (3): study by Glassner et al. at NREL [60], *Figures reproduced with the permission of Springer (license number: 3413831485326) and Elsevier Publications (license number: 3415470571765)*

Nomenclature

d_1, d_2, d_3	dummy variables, dimensionless
a_1, a_2, a_3	empirical coefficients, dimensionless
x, y	empirical coefficients, dimensionless
α, β	empirical coefficients, dimensionless
m	number of cost group, from 1 to 7
e	combined efficiency of motor-pump drivers, %
g	gravitational acceleration, m s^{-2}
k	von Karman constant (0.4 in this paper)
s	specific gravity (the ratio of density to density of water), dimensionless
d	representative chip dimension defined, m
n	fluid behavior index, dimensionless
z	distance from the pipe invert, m
v	kinematic viscosity of the carrier fluid, m^2 s^{-1}
crf	charge on capital investment to cover interest, depreciation, etc.
$r.m.s.$	root mean square
K	fluid consistency index, units consistent with those in generalized Reynolds number
A	empirical constant, dimensionless
E	empirical constant, dimensionless
P	ratio of characteristic particle dimension (here d_{50}) to pipe diameter, dimensionless
D	pipe internal diameter, m
W	tonnes per day of oven-dry chips, t d^{-1} dry biomass
L	length of the pipeline, km
S	solid particle shape factor, dimensionless
$\Delta H\ L^{-1}$	longitudinal pressure gradient, kPa m^{-1}
MC	Mass fraction of water in the solid, %
LHV	lower heating value, J kg^{-1}
A_S	solid particle area, mm^2
X_1	energy cost, \$ $t^{-1}km^{-1}$
X_2	installed cost of pipeline and its appurtenance (valves, meters, flow controls), \$ $t^{-1}km^{-1}$
X_3	installed cost of pump station, \$ $t^{-1}km^{-1}$
X_4	installed cost of injection and separation system, \$ $t^{-1}km^{-1}$
X_5	cost of fixed salaries, wages, and operations that are independent of length of pipeline or number of pump stations, \$ $t^{-1}km^{-1}$
X_6	cost of variable salaries, wages, and operations that are dependent on the length of the pipeline and the number of pumping stations, \$ $t^{-1}km^{-1}$
X_7	cost of water treatment, \$ $t^{-1}km^{-1}$
X_m	each of the 7 cost groups, \$ $t^{-1}km^{-1}$
X_T	total cost of pipeline hydro-transport, \$ $t^{-1}km^{-1}$
X_{gw}	geometric mean width, mm
X_{gl}	geometric mean length, mm
R_1	cost of electrical energy, \$ kWh^{-1}
R_2	installed cost of pipeline, including right-of-way, \$ $m^{-1}km^{-1}$
R_3	cost of pump station and controls, \$ per installed kW
R_4	cost of wood chip injection system, \$ $t^{-1}d^{-1}$ dry biomass
R_5	cost of wood chip separation system, \$ $t^{-1}d^{-1}$ dry biomass
R_6	annual cost of fixed salaries, wages, and operation maintenance, exclusive of pipeline maintenance and pump station operation

R_7	annual wages, salaries, etc., for pump stations, \$ per pump station
R_8	annual maintenance cost of pipeline, \$ km^{-1}
R_9	cost of water and treatment, \$ Mm^{-3}
d_{50}	particle length at respective 50% cumulative number fraction of particles, mm
Z_T	difference in elevation between inlet and discharge of the pipe, m
S_m	specific gravity of wood chip-water mixture, dimensionless
H_T	head due to friction and difference in elevation, m_{H2O} km^{-1}
H_{sa}	total head developed per pump station, m_{H2O}
S_{odc}	specific gravity of oven-dried wood chips, dimensionless
C_v	solid volume content, %
C_m	solid mass content, %
C_d	particle drag coefficient, dimensionless
C_{top}	solid volume content at $z\ D^{-1}$ = 0.92 (z is the vertical position from the pipe bottom)
C_{mid}	solid volume content at $z\ D^{-1}$ = 0.5
M_s	mass of solid particle sample, kg
Q_l	carrier liquid (water) flow rate, m^3 s^{-1}
Q_s	wood chip flow rate, m^3 s^{-1}
$Q_{s,max}$	maximum wood chip flow rate, m^3 s^{-1}
Re_f	Reynolds number of water and suspended fine particles flow, dimensionless
Re_g	generalized Reynolds number, dimensionless
Re_m	mixture Reynolds number, dimensionless
Re_w	clear water Reynolds number, dimensionless
V_m	mean mixture velocity, m s^{-1}
V_∞	particle settling velocity, m s^{-1}
i_m	hydraulic gradient of mixture, $m_{H2O}\ m_{pipe}^{-1}$
i_w	hydraulic gradient of water, $m_{H2O}\ m_{pipe}^{-1}$
i_f	hydraulic gradient of water and suspended fine particles flow, $m_{H2O}\ m_{pipe}^{-1}$
f_F	Fanning friction factor, dimensionless
f_D	Darcy-Weisbach friction factor, dimensionless
f_m	mixture friction factor, dimensionless
f_f	friction coefficient of the water and fins particles flow, dimensionless
f_w	clear water friction factor, dimensionless
μ_0	dynamic viscosity of clear water, N.s m^{-2}
μ_m	viscosity of mixture, N.s m^{-2}
ρ_p	density of solid particle, kg m^{-3}
ρ_f	density of water and suspended fine particles mixture, kg m^{-3}
ρ_w	density of clear water, kg m^{-3}
ρ_m	density of mixture, kg m^{-3}
φ	the ratio of mixture viscosity to clear water viscosity, dimensionless
λ	parameter dependent of the flakiness of the particle, dimensionless

Table 1: Historical development of biomass slurry pipelines

Organization	Time	Location	Biomass Feedstock	Pipeline Length	Pipeline Diameter	Particle Dimension	Reference No.
D.T. Elliott and W.H. de Montmorency Pulp and Paper Research Institute of Canada	1958	Quebec, Canada	Spruce and balsam fir wood chips	160 m	200 mm	d_{50} = 6.4 mm	[10, 21]
Shell Pipeline Company	1962	Texas, U.S.	Wood chips	1220 m	200 mm	---	[22, 23]
R.R. Faddick Queen's University	1963	Ontario, Canada	Wood chips	---	100 mm	---	[11]
Brebner Queen's University	1964	Ontario, Canada	Jack pine and spruce wood chips	120 m	100 mm	d_{50} = 6.4 mm	[24]
Georgian Research Institute of Forest Industry	1964	Georgia, Soviet Union	Wood chips	48 m	150 mm	---	[25]
A co-operative enterprise of 20 companies	1964	Ontario, Canada	Wood chips	610 m	150 mm 200 mm 250 mm	15 mm×12 mm×6 mm	[5, 26, 27]
E.J. Wasp Bechtel Crop.	1967	California, U.S.	Wood chips	---	200 mm	19 mm×12.7 mm×2.54 mm	[28]
A. Soucy Laval University	1967	Quebec, Canada	Wood chips	---	150 mm	---	[29]
R.R. Faddick Montana State University	1970	Montana, U.S.	Uniform-sized plastic chips	210 m	75 mm 100 mm	12.7 mm×9.5 mm×2.54 mm	[30]
J.L. Gow Montana State University	1971	Montana, U.S.	Lodgepole pine wood chips	---	100 mm 150 mm	d_{50} = 9.5 mm	[12]
W.A. Hunt Montana State University	1976	Montana, U.S	Lodgepole pine wood chips	91 m 183 m	200 mm 300 mm	d_{50} = 28.4 mm	[22]
University of Alberta	2007-2015	Alberta, Canada	Wheat straw Corn stover	25 m	50 mm	d_{50} = 1.9 mm to 8.3 mm	[16-19, 31-33]

Table 2: Data for a generalized economic model by Hunt [53] (Originally presented in imperial units). *Table reproduced with the permission of Forest Products Research Society (license number: 3413841423702)*

Item	Value	Unit	Item	Value	Unit	Item	Value	Unit
crf	0.200		S_{odc}	0.40		R_5	107.8	$ $t^{-1}d^{-1}$
e	0.650		Z_T	0	m	R_6	323,400	$ y^{-1}
f	0.018		R_1	0.05	$ kWh^{-1}	R_7	51,000	$ per pump station
g	9.8	$m\ s^{-2}$	R_2	615,600	$ $m^{-1}km^{-1}$	R_8	425.3	$ $km^{-1}y^{-1}$
H_{sa}	244	m	R_3	1000	$ kW^{-1}	R_9	0.1423	$ m^{-3}
M	1.80		R_4	53.9	$ $t^{-1}d^{-1}$			

Table 3: Economic and technical parameters used by Kumar et al. to estimate the capital and operating costs of a wood chip-water mixture pipeline [13], *Table reproduced with the permission of Springer Publication (license number: 3413831485326)*

Item	**Value**	**Unit**
Life of pipeline	30	y
Contingency cost	20	% of total cost
Engineering cost	10	% of total capital cost
Discount rate	10	%
Operating factor	0.85	
Power cost	50	$ MWh^{-1}
Velocity of slurry	1.5	m s^{-1}
Velocity of water in water return line	2.0	m s^{-1}
Maximum pressure	4100	kPa
Pump efficiency	80	%
Scale factor applied to inlet, outlet, and booster station facilities excluding pumps	0.75	