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Review

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 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.

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 fibers 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

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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
ν	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

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 fiber is not a natural biomass but a mechanically or chemically processed biomass, and, therefore, its hydro-transport is