BIOSYSTEMS ENGINEERING 127 (2014) 144–158

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Development of correlations for the flow of agricultural residues as slurries in pipes for Bio-refining

Mahdi Vaezi, Amit Kumar*

4-9 Mechanical Engineering Building, University of Alberta, Edmonton, AB, Canada, T6G 2G8

ARTICLE INFO

Article history:
Received 18 June 2014
Received in revised form
17 August 2014
Accepted 28 August 2014
Published online 21 September 2014

Keywords:
Biomass
Non-wood fibres
Slurry pipeline
Numerical modelling
Regression analysis
Scale-up

Pipeline hydrotransport of agricultural residue in a carrier liquid could be an economically viable alternative to replace truck delivery of biomass materials, as well as encouraging the increase in scale of bio-refineries. The feasibility of this concept, together with friction loss behaviour and corresponding mechanisms of biomass slurry flows through pipelines, was previously studied by the authors. A 50 mm diameter, 25 m long pipeline facility was used to measure the longitudinal pressure gradient of wheat straw and corn stover slurries over a range of particle dimensions, slurry solid mass fractions, and slurry velocities. Econometric software and a nonlinear least square regression model were used to analyse the measured pressure gradients and an empirical correlation was proposed to predict slurry pressure gradients as a function of slurry specifications and operating conditions. The correlation was then modified using scale-up methods to account for the effects of pipe diameter. The pressure gradient was found to be proportional to the pipe diameter to the power of −1.2. The final correlation was able to predict the longitudinal pressure gradient of the flow of agricultural residues (i.e., non-wood fibres) as biomass slurries in pipes and, with a small uncertainty (<10%), could be applied to design commercial pipelines to hydraulically transport various agricultural residue biomass slurries. This knowledge of the slurry flow pressure gradient is essential to specify slurry pumps, determine the number of booster stations, and estimate the capital and operational costs of a slurry pipeline.

1. Introduction

Today, biomass-based fuels and energy are of increasing interest as renewable and environmentally friendly alternatives to fossil fuels and the energy derived from them. Although dry biomass production of 220 billion tonnes.yr^{-1} worldwide (Hall & Rao, 1999) can theoretically provide adequate feedstock for bioenergy production, in practice, bio-based energy facilities are built with capacities significantly below that of the typical capacities of petroleum refineries (Aden et al., 2002). This is mainly due to significant and scale-independent truck delivery costs (US \$ tonne^{-1} km^{-1}) and the corresponding traffic congestion issues (Kumar, Cameron, & Flynn, 2005a, 2005b). Pipeline hydraulic transport (hydrotransport) of biomass

* Corresponding author. Tel.: +1 780 492 7797; fax: +1 780 492 2200.
E-mail address: amit.kumar@ualberta.ca (A. Kumar).
http://dx.doi.org/10.1016/j.biosystemseng.2014.08.018

Nomenclature

D	Pipe internal diameter, m
D_0	Experimental setup pipe diameter, 0.0508 m
V	slurry bulk velocity, m s^{-1}
V_w	slurry bulk velocity at the onset of drag reduction, m s^{-1}
C_d	Dry solid mass fraction, %
C_s	Saturated solid mass fraction, %
L	Pipe length, m
$\Delta H\ L^{-1}$	Longitudinal pressure gradient in the pipe, kPa m^{-1}
N_i	Number of particles of a particular distinct dimension, dimensionless
X_i	Distinct length of particle, mm
X_n	Nominal particle length, mm
X_{gl}	Geometric mean length, mm
X_{gw}	Geometric mean width, mm
X_{gth}	Geometric mean thickness, mm
S	Solid particle shape factor, dimensionless
A_s	Solid particle area, mm^2
M_s	Mass of solid particle sample, kg
MC	Moisture content or water mass fraction, %
X	Experimental exponent for flow in smooth/rough pipes, dimensionless
I	Pressure gradient, kPa m^{-1}
i_w	Pressure gradient of the clear water, kPa m^{-1}
i_n	Pressure gradient predicted by the numerical model, kPa m^{-1}
i_{exp}	Pressure gradient experimentally measured, kPa m^{-1}
i_s	Pressure gradient predicted by the CSIR method, kPa m^{-1}
d_{50}	Particle median length, mm
p, q, r, k	Constants
m, n, j	Dummy variables
$\alpha, \beta, \gamma, \delta$	Constants
Λ	Parameter dependent of the flakiness of the particle, dimensionless
ρ_f	Density of carrier fluid, kg m^{-3}
ρ_s	Density of slurry, kg m^{-3}
ρ_p	Density of solid particle, kg m^{-3}
μ_f	Viscosity of carrier fluid, Pa s
σ_{gl}	Geometric mean length standard deviation, mm
σ_{gw}	Geometric mean width standard deviation, mm
σ_{gth}	Geometric mean thickness standard deviation, mm
R^2	A statistical measure of how close the data are to the fitted regression line
Adjusted R^2	Compares the explanatory power of regression models that contain different numbers of predictors

materials in a carrier liquid can be considered as an alternative approach to enable biomass-based energy facilities to achieve higher capacities. This not only has the benefits of economies of scale (Kumar, Cameron, & Flynn, 2004), but also reduces the traffic congestion issues of overland transportation.

Among the variety of biomass materials, lignocellulosic biomass, which includes materials such as agricultural residues (e.g., wheat straw, corn stover) and forestry residues, has a significant potential to produce bioenergy – more specifically, liquid fuels. Not only does lignocellulosic biomass not interfere with food security, but liquid fuel production is considered an alternative use of these residues. It is also of great importance in both rural and urban areas in terms of energy security, environmental concerns, employment opportunities, and agricultural development. There have been only a few techno-economic analyses of pipeline transport of lignocellulosic biomass. These studies compared the cost of pipeline hydro-transport with truck delivery as well (Kumar et al., 2004; Kumar, Cameron, & Flynn, 2005a, 2005b). It was shown that one-way pipeline hydrotransport of corn stover at a 4% dry-matter solid mass fraction costs less than truck delivery at capacities more than 1.4 M dry tonnes yr^{-1} when compared to a mid-range trucking cost of US $0.1167 dry tonne^{-1} km^{-1}. However, these studies were based on the assumption that the pressure drop in the pipeline transport of agricultural residue as biomass slurries (i.e., chopped agricultural residue biomass-water mixture) was the same as the transport of wood chip-water mixtures along a pipeline. At that time no information was available, either in terms of experimental results or empirical correlations, on the pipeline hydro-transport of agricultural residue biomass. However, recently, Luk et al. (Luk, Mohammadabadi, & Kumar, 2014) and Vaezi and others (Vaezi, Katta, & Kumar, 2014; Vaezi & Kumar, 2014a; Vaezi, Pandey, Kumar, & Bhattacharyya, 2013) have experimentally investigated the pipeline hydrotransport of wheat straw and corn stover along a 25 m long, 50 mm diameter closed-circuit lab-scale pipeline facility. In 2013 Vaezi et al. studied wheat straw and corn stover morphology and its impact on mechanical behaviour and frictional pressure gradients[1] of corresponding solid-water mixtures (slurries) in a pipeline (Vaezi et al., 2013). They also studied the mechanical feasibility of agricultural residue biomass pipeline hydrotransport, investigated friction loss behaviour of wheat straw and corn stover slurries through pipelines (Vaezi et al., 2014), and evaluated the performance of centrifugal slurry pumps while handling agricultural residue biomass slurries (Vaezi & Kumar, 2014a).

To design an industrial-scale pipeline for the hydrotransport of agricultural residues for use as biomass fuels, it is necessary to understand how the slurry pressure gradient changes with slurry specifications (i.e., biomass type, particle size, slurry solid mass fraction, and slurry temperature) and operating conditions (i.e., pumping velocity, pipe diameter, and pipe roughness). This knowledge is essential to size the slurry pumps, determine the number of booster stations, and

[1] Frictional head loss or energy dissipated as heat due to friction between the pipe wall and fluid or internally within the fluid by turbulence.