Available online at www.sciencedirect.com

ScienceDirect

http://www.elsevier.com/locate/biombioe

The flow of wheat straw suspensions in an open-impeller centrifugal pump

Mahdi Vaezi, Amit Kumar *

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

ARTICLE INFO

Article history:
Received 3 April 2014
Received in revised form
16 June 2014
Accepted 6 July 2014
Available online

Keywords:
Triticum sativum
Fibrous particles
Slurry
Pipeline
Centrifugal pumps
Performance evaluation

ABSTRACT

A laboratory-scale closed-circuit pipeline facility was modified to experimentally investigate the effects of pumping slurries of wheat straw and corn stover particles on the performance characteristics of a centrifugal slurry pumps. The effects of particle size and slurry solid mass content (concentration) on head, efficiency, and power consumption of a centrifugal slurry pumps were studied. In a clear contrast to the general performance of centrifugal slurry pumps in conventional solid–liquid systems, the total head height increased with an increase in slurry solid mass content due to several reasons including unique friction loss behavior (i.e., drag reducing feature) of fibrous particles slurries in pipelines. In addition, small size fibrous particles increased the pump efficiency more than the efficiency of the same pump handling pure water only. A correlation was finally proposed to predict the reduction in head while centrifugally pumping fibrous agricultural residue biomass (wheat straw, corn stover) slurries, compared to the head produced while handling pure water only. The results could be used in the design and operation of centrifugal slurry pumps to transport fibrous agricultural residue biomass materials. However, the effects of other parameters like air in the system and anaerobic problems should be taken into account too.

1. Introduction

Thanks to its renewability, abundant availability, and carbon dioxide neutrality, biomass is considered to be one of the most promising renewable resources for the production of fuels and chemicals. However, biomass-based fuel production facilities come with capacities significantly below that of current petroleum refineries [1] mainly due to substantial (and scale-independent) truck delivery costs and corresponding traffic congestion issues [2]. Pipeline transport of agricultural residue biomass materials via a carrier liquid (i.e., hydraulic transport or hydro-transport) can be considered as an alternative approach to enable bio-based energy facilities to achieve higher capacities. The benefits to hydro-transport are not only the economies of scale [3] but also in the easing of community concerns and the traffic congestion issues of land transportation.

Following a series of techno-economic analyses of pipeline hydro-transport of wood chips and corn stover biomass materials [2], a lab-scale closed-circuit pipeline facility was designed and fabricated. Slurries of agricultural residue biomass particles (wheat straw and corn stover) were first prepared over a wide range of particle sizes and dry-matter

* *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.biombioe.2014.07.009
0961-9534/

Nomenclature

PSD	particle size distribution
MC	wet-basis water mass content (moisture content), %
NLS	non-linear least squares
ARMA	autoregressive moving average
L_{MD}	electric motor load – data provided by manufacturer
L_{FDE}	electric motor load – data provided by Facility Dynamic Engineering
L_{NRC}	electric motor load – data provided by Natural Resource Canada
H	electric motor efficiency, %
Q	flow rate, $m^3\ s^{-1}$
A_s	solid particle area, mm^2
S_x	standard deviation of the measurements ($S_x = \sqrt{\sum (x_i - \bar{x})^2/n-1}$), corresponding unit
P_x	precision uncertainty ($P_x = t_{\alpha/2,\upsilon}(S_x/\sqrt{n})$), corresponding unit
B_x	bias uncertainty, corresponding unit
U_x	total uncertainty ($U_x = \sqrt{\sum B_x^2 + P_x^2}$), corresponding unit
V_m	solid–liquid mixture velocity, m s^{-1}
M_s	mass of solid particle sample, g
X_{gl}	geometric mean length, mm
$X_{gl,width}$	geometric mean width, mm
D_{pipe}	pipe internal diameter, m
Re_g	generalized Reynolds number, ($Re_g = \rho_m V_m D_{pipe}/\mu_f$)
C_w	saturated solid mass content, %
C_v	saturated solid volume content, %
$H_{C\%}$	head height produced by the centrifugal pump for C_w% solid mass content slurry, kPa
H_r	Head ratio : $\frac{\text{head developed with slurry at any flow rate}}{\text{head developed with water at the same flow rate}}$
E_r	Efficiency ratio : $\frac{\text{efficiency of the pump for slurry at any flow rate}}{\text{efficiency of the pump for water at the same flow rate}}$
K_H	head reduction factor
S_p	specific gravity of saturated solid particles
D_{imp}	pump impeller exit diameter, mm
n	number of measurements
d_{50}	median length, mm
λ	thickness factor
ρ_s	solid particle density, kg m^{-3}
ρ_m	density of mixture, kg m^{-3}
σ_{gl}	geometric mean length standard deviation, mm
$\sigma_{gl,width}$	geometric mean width standard deviation, mm
μ_f	dynamic viscosity of carrier fluid, Pa s
$t_{\alpha/2,v}$	t-distribution with α = 1–95, %confidence and $\upsilon = n-1$

solid mass contents. The slurry was then pumped through the closed-circuit pipeline using a centrifugal slurry pump to investigate the feasibility of biomass pipeline hydro-transport and measure the mechanical parameters of slurry flow, e.g., friction loss and pump performance characteristics.

The performance of centrifugal slurry pumps has been the subject of several studies. Conventional Newtonian and non-Newtonian solid–liquid mixtures have been used to investigate the effects of solid particles' specifications (i.e., size, specific gravity (density of particle relative to density of water), drag coefficient), slurry specifications (i.e., rheological property, solid mass content), and pump features (i.e., impeller size and operating conditions) on the power consumed, the head produced, and the efficiency achieved by the centrifugal slurry pump [4–8]. In general, lower head and efficiency were reported for the pumps handling slurries of medium- and coarse-size particles in comparison to the pumps handling pure water only, which has been attributed to the difference in the velocity of liquid and solids leaving the impeller [9], as well as to the additional friction loss in the flow passages due to suspended solids [10]. Gandhi et al. [4] studied the performance characteristics of a couple of small and large centrifugal slurry pumps handling slurries of fly ash, bed ash, and zinc tailings, where a decrease in head and efficiency of the pump was observed with increase in solid mass content, particle size, and slurry viscosity. Using 19 various basic pump designs, Horo and Niskanen [5,8] experimentally investigated pumping of groundwood pulp (natural fiber used for pulp and paper production) through centrifugal pump and studied the effect of fibers on suction and pumping capacity, and the effect of air on the pump operation. They reported that the same, or higher than, the head height produced with pure water could be achieved with groundwood pulp at solid volume contents up to 7.0% provided a centrifugal pump specifically designed for pumping pulp was used.

Several attempts have been made to correlate the experimental data with solid particle properties, solid mass content, and pump specifications [11–16]. These correlations are dependent on pump size, properties of the slurries, and solid particles specifications, and are not universally applicable. The majority of the literature published on the performance characteristics of centrifugal slurry pumps used conventional solid particles with median lengths of 0.042 mm [4] for fly ash to 2.2 mm for sand [7] and density of 1480 kg m^{-3} for coal [15] to 6240 kg m^{-3} for mild steel [17]. The agricultural residue biomass particles studied here were noticeably larger (from 1.9 to 8.3 mm) compared to fly ash particles and had much smaller density (saturated) of 1050 kg m^3. Such particle specifications, together with several unusual particle characteristics (e.g., wide size distribution; extreme shapes; fibrous, pliable, flexible, and asymmetric nature; potential for forming networks; ability to take up the carrier fluid) [18] give rise to a variety of mechanisms in slurry flow, e.g., drag reduction [19] which are often not encountered in classical solid–liquid systems. Typical fibrous particles slurry flows (e.g., slurry of natural and synthetic fibers of several micrometers to 5.0 mm in length and aspect ratios of 25 to several hundred) with progressively increasing fiber populations (i.e., slurry solid mass content) exhibit similar phenomena as well, i.e., drag reduction, particularly when fibers in suspension are subject