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Application of high-frequency impedancemetry approach in measuring the deposition velocities of biomass and sand slurry flows in pipelines

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\textbf{A B S T R A C T}

Since the lower limit to operating velocities in slurry transport systems is influenced by deposition conditions, measuring the “deposition velocity” is an essential step in slurry pipelines’ design and operation. This study proposes a new experimental technique in measuring deposition velocities in slurry pipeline transport called the high-frequency impedancemetry approach. This non-invasive technique of measuring electrical properties of substances, based on their frequency-dependent behavior, was applied using a 16-electrode impedancemetry device on a 25\,m long closed-circuit pipeline to measure the deposition velocities of sand- and biomass–water mixture flows. Slurries of play and gravel sands, as well as wheat straw and wood chips biomass feedstock, were prepared over a range of concentrations (1.5–20 wt\% dry-matter), and deposition velocities were measured over a wide range of operating velocities (0.04–4.5 m/s). Experimental measurements for sand–water mixtures were found to be in good agreement with empirical correlations derived previously through various analytical and mathematical techniques. In addition, for the first time, the deposition velocities for biomass–water mixtures were measured and found to be in the range of 0.21–0.8 m/s; surprisingly well below the common range of commercial pipelines’ operating velocities, i.e., 1.4–3.0 m/s.

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1. Introduction

Slurry (solid–liquid mixture) pipeline transport is a commercially viable mode of delivering solid commodities as an alternate to truck and rail. Since the 1960s, several commercial slurry pipelines have been constructed to hydraulically transport a variety of solids including coal (Abulnaga, 2002; Coffey and Partridge, 1982; Lahiri, 2009), limestone (Abulnaga, 2002; Venton, 1982), iron ore (Mariano De Souza et al., 2004), phosphate concentrate (Abulnaga, 2002; Weston and Worthen, 1987), and bitumen (Winter et al., 2003). However, slurry pipeline transport is a complex process that, as noted by Nardi (1959), to successfully design a pipeline to hydrotransport solids, designers need to consider as many as 32 variables (including 8 physical characteristics of the solid, 10 physical characteristics of the slurry, and 14 factors in design data) all at the same time. Predicting the prevailing flow regime and the longitudinal friction loss, as well as estimating deposition velocity, are the main technical issues to be addressed before constructing a slurry pipeline (Turian et al., 1987). The deposition velocity, also referred to as “the minimum carrying velocity” and “the limiting deposit velocity,” is the lower limit to operating velocities for slurry transport systems with settling (heterogeneous) slurries containing particles predominantly larger than 50–70\,\mu m (Grzina et al., 2009). Deposition velocity is commonly defined as “the minimum velocity demarcating flows in which the solids form a bed at the bottom of the pipe from fully suspended flows” (Groskar and Turian, 1980).

There have been several analytical correlations proposed to predict the deposition velocity for slurry transport in pipelines. After conducting a series of experiments, Durand (1953) and Durand and Condolios

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Table 1 – Comparison of published deposition velocity correlations in slurry transport.

| No. | Authors | \( f(C_v, s) \) | \( k^2 \) | \( l \) | \( m \) | \( \hat{D}^n \); RMS \(^h \)
<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Durand and Condolios (1952)</td>
<td>1.153 ( (C_v = 0.0197) )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.3653; 0.4074 for ( f(C_v, s) = 1.2 )</td>
</tr>
<tr>
<td>2</td>
<td>Wasp et al. (1977)</td>
<td>3.399 ( C_v^{0.2156} )</td>
<td>0</td>
<td>0</td>
<td>1/6</td>
<td>26.68; 0.3750</td>
</tr>
<tr>
<td>3</td>
<td>Knoroz (reported by Sasic and Marjanovic, 1978)</td>
<td>0.8165 ( C_v^{1.6} )</td>
<td>-0.5</td>
<td>0</td>
<td>-1/12</td>
<td>51.01; 0.6695</td>
</tr>
<tr>
<td>4</td>
<td>Zandi and Govatos (1967)</td>
<td>( 20C_v^{1/2} )</td>
<td>-1/4</td>
<td>0</td>
<td>0</td>
<td>50.02; 0.6521</td>
</tr>
<tr>
<td>5</td>
<td>Larsen (1968)</td>
<td>2.9818 ( C_v^{1/4} )</td>
<td>-1/4</td>
<td>0</td>
<td>0</td>
<td>45.22; 0.6090</td>
</tr>
<tr>
<td>6</td>
<td>Shook (1969)</td>
<td>2.4328 ( s )</td>
<td>-0.25</td>
<td>0</td>
<td>0</td>
<td>34.50; 0.5059</td>
</tr>
<tr>
<td>7</td>
<td>Oroskar and Turian (1980)</td>
<td>1.141 ( C_v^{(1 - C_v)^{2m - 1}} )</td>
<td>0</td>
<td>1/15</td>
<td>0</td>
<td>25.94; 0.4331</td>
</tr>
</tbody>
</table>

\(^a\) \( D_v (\%)dev \) = \left( \frac{C_{max} - C_{min}}{C_{avg}} \right) \times 100 \text{ and } \hat{D} = \text{Abs avg } \%\text{dev} = \sum_{i=1}^{N} \frac{|Dv_i|}{P}.

\(^b\) \text{RMS} = \left\{ \sum_{i=1}^{N} \left( \frac{C_{max} - C_{min}}{C_{avg}} \right)^2 \right\}^{0.5}.

\(^c\) All \( k \), \( l \), and \( m \) coefficients are adopted from Durand and Condolios (1952) reported by Oroskar and Turian (1980).
Following the electrical resistance tomographic (ERT) approach (see, for instance, (Dickin and Wang, 1996)), Fangary et al. (1998) used a 16-electrode sensor system with a current injection amplitude of 5 mA at a frequency of 10 kHz together with a back-projection image reconstruction algorithm to monitor the thickness of solids deposited on the base of a horizontal pipe. Fangary managed to detect the transition from a dispersed to a salting suspension. The latter produced a detectable perturbation on the reconstructed conductivity map at the bottom of the pipe cross section due to a change in the mean solid concentration in the flowing bulk suspension that was distinct from that in the settling region.

All four experimental approaches discussed above, although effective, come with inadequacies: Gillees and Shook (1991) reported ~10% error in visual observations compared to densitometer measurements. With gamma ray densitometry, a compromise must be made between accuracy and applicability. The larger aperture brings about higher intensity/accuracy but limits the measurement to the parts with sufficiently large test areas of constant thickness. In addition, safety requirements/regulations to install/operate gamma ray densitometry are restrictive (Schlierer, 2000). With pressure transducers, if the flush diaphragm type is not used, it is challenges to prevent solid particles from disturbing/stopping measurements. Furthermore, at lower slurry flow rates, friction losses are too small to be accurately detected by typical transducers (Vaezi et al., 2014a). Finally, the ERT (electrical resistivity tomography) system is sophisticated (comprised of sensors, signal generator, multiplexer, digital de-modulation, etc.) and costly, and data collection strategies and image reconstruction algorithms are difficult to apply. In addition, the ERT approach, to be applicable, requires a significant electrical conductivity difference between solid particles and fluid (Yenjaichon et al., 2011).

The high-frequency impedancemetry approach is a non-invasive technique of measuring electrical properties of substances based on their frequency-dependent behavior. Although it has been widely used in biology and biotechnology (Dezenzios et al., 1994; Dheilly et al., 2008), as well as in a variety of clinical applications from hematology (Brahimi et al., 2019) to nephrology (Caillette et al., 1994; Snye et al., 1994) to nutrition (Bott, 2006; Ellis et al., 2000), the aim here was to develop and validate a methodology to apply high-frequency impedancemetry in the pipeline transport of solid commodities to measure the slurry flows’ deposition velocities. Accordingly, a 16-electrode impedancemetry device was designed, fabricated, and installed on a 25 m and 50 mm in diameter closed-loop pipeline facility to measure the deposition velocity of sand–water mixtures, as well as biomass–water mixture flows. Unlike previous deposition velocity measurement techniques, the device proposed here does not disturb/stop the slurry flow and is simple and economical to fabricate (a minimum of two conductive electrodes on a non-conductive piece of pipe are needed), easy to operate (no programing or post-analysis required), easy to mount on the pipeline (could be flanged anywhere along the pipeline), applicable to all the suspensions conducting electricity, and capable of accurately measuring slurry deposition velocities as low as 0.04 m/s. In light of all these features, the high-frequency impedancemetry approach can become the standard deposition velocity measurement technique. Following are the specific objectives of the present research study:

- Proposing application of high-frequency impedancemetry technique in experimentally measuring deposition velocities of slurry (i.e., solid–liquid mixture) flows in pipes,
- Designing, fabricating, installing, and calibrating a 16-electrode impedancemetry device on a lab-scale closed-circuit pipeline facility,
- Proving the viability of the proposed high-frequency impedancemetry approach in measuring the deposition velocities of slurry flows in pipes in a simple, fast, and accurate manner, and
- Measuring the deposition velocities of forest- and agricultural residue-water mixture flows in pipelines hydro-transport of biomass feedstock for biofuel production purposes.

## 2. Methodology

### 2.1. Commercial pipeline operating velocity

The commercial operating velocity for pipelines has been reported differently for various commodities. To prevent erosion by solids, noise, or water hammer caused by quickly closing a valve, pipeline operating velocities must not exceed a maximum, nor should they drop below a minimum in order to keep the line swept clear of entrained solids and liquids. The maximum and minimum velocities are normally set to 4.5 m/s and 0.9 m/s, respectively (Abulinaga, 2002). However, the acceptable range commonly practiced in industry is 1.4–3.0 m/s (Leitch, 2006). Operating (i.e., slurry) velocities experimented within this study range from 0.04 to 4.5 m/s, which covers well the range used in commercial applications for all sorts of commodities (oil sands, iron ore, coal, etc.) reported in earlier studies (Coffey and Partridge, 1982; Venton, 1982; Mariano De Souza et al., 2004; Winter et al., 2003). It is worth mentioning that investigating other velocity-dependent phenomena such as erosion is out of the scope of the present research.

### 2.2. Experimental setup and slurry preparation

Three types of particles — sand, agricultural residue biomass (i.e., wheat straw), and forest residue biomass (i.e., wood chips) — were tested. The solid particles were chosen purposely since (1) pumping sand–liquid mixtures is commonly practiced in the oil sands and dredging industries (Matousek, 2001, 2002), (2) there exist a large body of experimental data previously published on sand–water mixture flows which will be used for comparison/validating purposes, (3) the bioenergy sector is investigating the technical and economic feasibility

<table>
<thead>
<tr>
<th>Particle</th>
<th>Type</th>
<th>Mass median particle diameter – d10 (mm)*</th>
<th>Particle density (kg/m³)</th>
<th>Slurry concentration (wt% – saturated)β,γ</th>
<th>Slurry concentration (wt% – dry)β</th>
<th>Slurry concentration (vol% – dry)β</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>Play sand</td>
<td>0.445</td>
<td>2650</td>
<td>NA</td>
<td>5</td>
<td>1.9–8.6</td>
</tr>
<tr>
<td></td>
<td>Environmental gravel sand</td>
<td>0.630</td>
<td></td>
<td></td>
<td>2–6.5</td>
<td>2–6.3</td>
</tr>
<tr>
<td></td>
<td>Fine wheat straw</td>
<td>4.81</td>
<td>1250</td>
<td>10–30</td>
<td>2–4.2</td>
<td>2–4.1</td>
</tr>
<tr>
<td></td>
<td>Large wheat straw</td>
<td>9.7</td>
<td>1450</td>
<td>10–40</td>
<td>3–13</td>
<td>2.2–9.6</td>
</tr>
<tr>
<td>Forest residue</td>
<td>Fine chips (aspen and poplar)</td>
<td>1.91</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Large chips (spruce and pine)</td>
<td>7.18</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Corresponding particle lengths in mm at respective 50% cumulative volume fraction of particles.

β With 82% saturated moisture content for agricultural residue and 70% for forest residue particles.

γ Maximum concentration tested was limited by the pipeline diameter and the pumping capacity.

## Table 2 - Properties of various sand and biomass particles and their corresponding water-based slurries.
of pipelining forest- and agricultural residue-water mixtures to bio-based energy facilities for the large-scale production of bio-fuels (Vaezi et al., 2013; Vaezi et al., 2014a; Vaezi, 2014b; Vaezi and Kumar, 2014; Vaezi et al., 2015). Play sand as well as environmental gravel sand (EGS) were supplied by Sil Industrial Minerals, wheat straw was collected from a farm in northern Alberta, Canada and Weyerhaeuser Pembina Timberslands Company provided large (spruce and pine) and small (aspen and poplar) wood chips. Table 2 gives the specifications of the particles. Size distributions of the particles are shown in Fig. 1.

A schematic illustration of the experimental setup is provided in Fig. 2. The setup is comprised of 25 m long, 50 mm ID, schedule 40 steel pipe with a clear acrylic section, long and short radius bends, and horizontal, inclined, and vertical orientations. The liquid (water) and solid particles were mixed to the desired concentration (see Table 2) in a vessel equipped with a 0.37 kW centrally placed mixer (EV6PS0M; Lightning Inc., Rochester, NY, USA) with a double, three-bladed impeller. The slurry flow was provided by a specifically designed 7.45 kW centrifugal pump (CD80M; Godwin Pumps Ltd., Bridgeport, NJ, US) coupled with a 7.45 kW induction electric motor (CC968A; Madison Industrial Equipment, Vancouver, BC, Canada) and controlled by a 14.9 kW variable frequency drive (VFD) controller (MA7200-2020-N1, TECO-Westinghouse Co.). Slurry temperature was monitored and adjusted to maintain an approximately isothermal condition (about 15 °C) using a double-tube heat exchanger. The setup was also equipped with an electromagnetic flow meter (FMG-401H; Omega Eng., Stamford, CT, USA), a resistance temperature detector (RTD-E; Omega Eng., Stamford, CT, USA), flush diaphragm low-pressure transmitters (PX42G7; Omega Eng., Stamford, CT, USA), and a watt transducer (PCS; Flex-Core, Columbus, OH, USA). The output signals from the equipment were recorded on a one-hundred-data-per-second basis on a data acquisition system comprised of a 4-channel current excitation module (NI9219; National Instrument Corp., Austin, TX, USA) and a data acquisition program (LabView V.9.0.1f2; National Instrument Corp., Austin, TX, USA).

Solid-liquid mixtures were prepared over a range of particle types (sand, agricultural residue, forest residue), particle dimensions (d50 from 0.4 to 9.7 mm), and slurry concentrations (from 1.5 to 20 wt% dry matter). Table 2 presents the range of the slurry concentrations restricted by mechanical constraints, e.g., pump power and pipe diameter. Forest and agricultural residue biomass slurries were circulated at high flow rates (4.5 m/s) for 8–12 h before stable mixture properties (the particle’s moisture content [MC] and dimensions, carrier liquid density and viscosity, mixture air content) and operating conditions (pressure and velocity fluctuations less than 1% per hour) were attained (Vaezi and Kumar, 2014). Measurements were then made on a slurry of a known particle type and size while the flow rate was decreased from 4.5 to 0.04 m/s using a variable frequency drive (VFD) controller and on the slurry concentration by adding clear water to the mixing vessel.

2.3. High-frequency impedancemetry approach

An impedancemetry device was designed and fabricated and mounted on one horizontal section of the pipeline setup (Fig. 2 — Section 4). The device is comprised of 16 electrodes (stainless steel cylinders 2.95 mm in diameter) with a wide base (20 mm long, 6 mm wide, 3 mm in depth) precisely inserted through the wall of a non-conductive plastic pipe (52.5 mm in diameter) to lie along the inner wall so as not to disrupt the slurry flow in any way (Fig. 3). On the sides of the measurement device, a non-reactive non-conductive plastic collar and a stainless steel tightening are used to ensure a tight seal between the collar and the measurement device. This device has flanges at each end to facilitate mounting and dismounting when/where needed (Fig. 3(d)).

Electrical impedance", or simply impedance, describes a measure of opposition to alternating current (AC); it extends the concept of resistance to AC circuits, describing not only the relative amplitudes of the voltage and current, but also the relative phases. The slurry, together with the impedancemetry device, formed a resistive-capacitive circuit with a capacitance independent of the slurry concentration. Since the capacitance reactance (impedance of the capacitor) is inversely proportional to the frequency of the applied voltage, a high-frequency voltage was applied here in order to cancel the capacitive effect (the reac-

---

1. On unit weight basis of dry-matte (0% moisture content) solid mass contents.
Fig. 2 – Pipeline facility in the Large Scale Fluids Lab. (1) mixing tank, (2) centrifugal slurry pump, (3) heat exchanger, (5) clear acrylic section, (4) impedancemetry device, (6) impedance measurement system (7) magnetic flow meter, (8) temperature sensor, (9) pressure transducer, (10) data logger, (11) watt transducer, (12) cooling unit.

Fig. 3 – (a) Schematic of the impedancemetry device with 16 electrodes, (b) side and cross sectional view of the impedancemetry device with 16 electrodes including the two adjacent electrodes (I & II) across which the impedance was measured, (c) electrical impedance measurement section fabricated in the Large Scale Fluids Lab, (d) Assembly of the measurement section including impedancemetry device, collars, tighteners, and flanges.

The impedance was measured across two adjacent electrodes (I and II — Fig. 3b) of the impedancemetry device. Measuring impedance along adjacent electrodes was found to give the least noise and fluctuations. Moreover, electrode I is the first one that comes in contact with the settling solid particles. Therefore, electrode I should necessarily be one of the two electrodes across which the impedance is measured.
Electrical connections were made from the dry side of the electrodes and then impedance was measured using the impedancemetry device along with (1) the impedancemetry setup circuit (Fig. 4a) and (2) the LCR meter (an electronic test equipment used to measure the inductance (L), capacitance (C), and resistance (R) — Fig. 4b). The programmable automatic LCR meter used here (PM 6304, Fluke Corp., Mississauga, ON, Canada) is an electronic device that measures the inductance (L), capacitance (C), and resistance (R) of a component. The magnitude of the impedance measured by both methods was different. This is because of the internal resistance of the individual devices in the circuit, as well as the differences in their measurement techniques.

2.4. Impedance measurement procedure

First, clear water was circulated throughout the experimental setup to measure the lower range of the impedance along electrodes I and II on the impedancemetry device. It was observed that the impedance of the circuit (Fig. 4a) changed with time (see Fig. 5a). Although the change in impedance was negligible, clear water was circulated in the loop before solid particles were added until a stable value of impedance was achieved. Initial built-up rust in the pipe was the main reason behind the variation of water impedance. Premeasured magnitudes of solids were then added to achieve favorite slurry concentration (see Table 2) while the slurry circulated at the maximum achievable flow rate to prevent settling along the pipeline bottom. Once stable mixture properties and operating conditions were attained (see Section 2.1), impedance and...
flow rate data were gathered using both the impedancemetry setup circuit and the LCR meter while the flow rate was gradually decreased from 4.5 to 0.04 m/s (the decrease in flow rate was made in steps of 0.5 m/s when there was no sign of solid deposition and in steps of 0.1 m/s when the formation of a moving bed was noticed). Deposition was observed visually as well in a section of transparent pipe (Fig. 2 — Section 5) whenever possible. Once the measurement of impedance at certain slurry concentration over the entire range of flow rates was complete, pumping velocity was increased back to the maximum of 4.5 m/s. While the slurry circulated at a high flow rate, either additional solid particles (in sand–water mixtures) or clear water (in biomass–water mixtures) was added to prepare the subsequent slurry concentration (although in practice solid particles are added to gradually increase the slurry concentration, in the case of biomass–water mixtures, because of the time it takes for the biomass solid particles to absorb water and become fully saturated, water was added to adjust/decrease the concentration). The entire experiment was then repeated the same way as described above. These steps were repeated until all solids concentrations were experimented with as per the ranges shown in Table 2.

The graphs in Fig. 5b show the general trends of impedance vs. velocity obtained through experimental measurements. The lower extreme represents fully suspended particles and the upper extreme corresponds to a stationary bed. The steep rise in the impedance is related to the formation of a moving bed. The same trend was reported by Gillies et al. (2000) and Gillies and Shook (1991) for variations in concentration along a horizontal chord close to the bottom of the pipe vs. pumping velocity.

The graphs were fitted to third order polynomial equations. The deposition velocity was then calculated at the point of inflection (by equating the second derivative of the polynomial function zero), implying a change in flow behavior from fully moving bed to part stationary bed with saltation, rolling, and ripple movement. Sample experimental measurements, corresponding third order polynomial trend lines and functions, and the point of inflection are marked on a schematic impedance-velocity graph on Fig. 5b.

3. Results and discussion

3.1. Sand–water mixtures

Fig. 6 shows the variation of the impedance vs. the slurry flow rate for 5 to 20 wt% play sand–water mixtures in the pipeline setup. By looking at the graphs, one can quickly make an engineering estimation of the deposition velocity around the point at which the concavity changes. A more accurate value was obtained by fitting a polynomial curve to the experimental points and calculating the point of inflection. The polynomials with the order of three were examined to find the appropriate curve that makes the best fit to the experimental measurements and comes with the highest coefficient of determination. To improve the overall fit of the estimated regression line, only the part of the line with a steep slope (corresponding to the formation of moving and stationary beds) was considered.

The applicability of the impedancemetry device, the accuracy of the impedancemetry setup, and the reliability of the high-frequency impedancemetry approach were investigated. Table 3 and Fig. 7a present the deposition velocities of sand–water mixtures containing coarse and fine particles measured using the impedancemetry device. A sharper increase in deposition velocity with increases in concentration is observed at lower concentrations for environmental gravel sand particles; i.e., 5–10 wt%. However, the range of concentrations tested for smaller play sand particles, was not wide enough to visually observe this effect. Adding more particles to the enclosed area of the pipe slows the slurry flow more than expected (hindered settling effect) and counteracts particle settling, which explains the smaller or reverse dependency of the deposition velocity on concentrations at higher concentrations. Turian et al. (1987) and Gillies et al. (2000) reported similar phenomena while investigating deposition velocities in pipeline flow of slurries. In terms of particle diameter, the deposition velocity has a rather weak dependence on particle diameter. The same conclusion has been
made by Turian et al. (1987), who suggest \( \nu_c \sim d^{-1} \) specially for large non-colloidal particles. This confirms the applicability of the impedancemetry device in measuring the deposition velocity of slurries of various particle diameters and concentrations.

To study the effect of temperature on deposition velocity, a play sand-water mixture was circulated through the pipeline at \( 28^\circ \text{C} \) and \( 42^\circ \text{C} \). Impedance magnitudes were then recorded over a range of slurry velocities and corrected according to the change in temperature over time using a correlation proposed by Giguere et al. (2008), as follows:

\[
R_{T,\text{ref}} = R_T [1 + a (T - T_{\text{ref}})]
\]

(2)
where $R_{T,\text{ref}}$ is the resistance at reference temperature $T_{\text{ref}}$, $R_T$ is the resistance at temperature $T$, and $\alpha$ is the thermal resistance coefficient ($\alpha = 0.02$ satisfies the equation in our experiment). It is observed on Fig. 7b that, after accounting for the change in impedance due to the change in temperature, the impedance values were almost identical in both slurry temperatures. This suggests that the change in impedance was merely caused by the change in slurry temperature and not any other change in the property of the liquid, e.g., viscosity of the carrier fluid. For consistency purposes, isothermal conditions (about 15°C) were retained here throughout the whole experiment.

The experimental values obtained here for the deposition velocities of various concentrations of play sand–water mixtures using the impedancemetry setup was re-measured with the LCR meter as well. Fig. 8 and Table 3 compare the two measurements and corresponding deviations. For the same slurry concentration, although there is a noticeable difference in the magnitude of impedance measured by the two techniques (see Section 2.2), corresponding deposition velocities are in excellent agreement with an average deviation of 2.22% only, thus confirming the accuracy and reliability of the impedancemetry setup.

The experimental approach proposed here was compared with empirical correlations proposed in literature. The deposition velocities experimentally measured were theoretically predicted as well using experimental facility dimensions and slurry properties plugged into five of 31 correlations reviewed by Turian et al. (1987) originally proposed by Oroskar and Turian (1980), Shook (1969), Larsen (1968), Zandi and Govatos (1967), and Knoroz originally reported by Sasic and Marjanovic (1978) for gravel- and play sand–water mixtures. Corresponding empirical correlations are reported in Table 1. As observed on Fig. 9, the deposition velocities obtained using these correlations turned out to be in good agreement with the experimental measurements with deviations ranging from 6.2 to +33% and average deviations of −8.3% for play sand–water mixtures and 6.9% for gravel sand–water mixtures. This is well below the average 92% deviation between empirical correlations and 864 experimentally measured deposition velocity data points (see Table 1) reported by Turian et al. (1987). This, as well, proves the viability of the high-frequency impedancemetry approach in measuring the deposition velocities of solid–liquid mixtures in pipes in a simple, fast, and accurate manner.

It is worth mentioning that although a change in the diameter of the pipeline would change the deposition velocities obtained here, the effect of the pipe diameter was not particularly studied here. The present research is focused on introducing a new approach of experimentally measuring deposition velocities and, for that reason, only one pipe diameter of 50 mm has been considered for validation and comparison purposes.

### 3.2. Agricultural and forest residues

The same approach as for the sand–water mixtures was applied to measure the deposition velocities in agricultural and forest residue–water mixtures. Fig. 10 shows the experimental measurements using the impedancemetry device as well as the LCR meter for slurries of various diameters of wheat straw and wood chip particles over a wide range of concentrations (1.5–13 wt% dry matter). A good agreement was found between impedancemetry and LCR measurements; in addition, a trend line similar to the lines for sand–water mixtures was obtained in all cases scenarios. Table 4 lists the deposition velocities for all the wheat straw- and wood chip-water mixtures experimented here. As it can be observed, the deposition velocities were relatively small, ranging from 0.21 to 0.8 m/s, and no meaningful relations were found between the slurry concentrations and the deposition velocities. The velocity ranges are well below the common range of operating velocities in industrial pipelines, i.e., 1.4–3.0 m/s (Abulnaga, 2002) (see Section 2.1). This, surprisingly, implies that while pumping biomass–water mixtures in pipelines under the conditions studied here (i.e., material type, particle size, slurry concentration, commercial velocity range), no deposition will be observed. This is good news for the pulp and paper and the biofuel sectors, which are actively exploring the option of replacing truck delivery of biomass feedstock by pipeline hydro-transport. Knowing that there are no deposition concerns considerably simplifies the design and operation of biomass slurry pipelines. To the best of the authors’ knowledge, this is the first time this feature is observed and reported.
Fig. 8 – Impedance vs. slurry velocity for play sand–water mixtures of various concentrations measured using the impedancemetry circuit and the LCR meter.

Fig. 9 – Experimental vs. numerical/empirical correlation results for the deposition velocities of (a) play sand–water mixtures and (b) gravel sand–water mixtures in pipes.
Fig. 10 – Impedance vs. slurry velocity for (a) 6.5 wt% dry-matter slurry of 4.8 mm wheat straw particles, (b) 4.2 wt% dry-matter slurry of 9.7 mm wheat straw particles, (c) 13.0 wt% dry-matter slurry of 1.9 mm wood chips particles, and (d) 3.0 wt% dry-matter slurry of 7.1 mm wood chips particles measured using the impedancemetry device.

Table 4 – Deposition velocity for various concentrations of biomass–water mixture flows measured using the impedancemetry setup.

<table>
<thead>
<tr>
<th>Particle type</th>
<th>Particle size</th>
<th>Slurry concentration (C_m, wt% – dry)</th>
<th>Deposition velocity (v_C, m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat straw</td>
<td>Fine (d_{50} = 4.81 mm)</td>
<td>2.0</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.2</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.5</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Large (d_{50} = 9.7 mm)</td>
<td>2.0</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.1</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.2</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.0</td>
<td>0.44</td>
</tr>
<tr>
<td>Wood chips</td>
<td>Fine (d_{50} = 1.91 mm)</td>
<td>6.2</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.5</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>Large (d_{50} = 7.18 mm)</td>
<td>1.5</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.0</td>
<td>0.57</td>
</tr>
</tbody>
</table>

4. Conclusion

The high-frequency impedancemetry technique was applied here for the first time to measure the slurry flow deposition velocity in pipeline transport of solids. A 16-electrode impedancemetry device was designed, fabricated, and installed on a 25 m long and 50 mm in diameter closed-loop pipeline facility to measure the deposition velocity of sand (play sand and environmental gravel sand)-water mixtures and biomass (wheat straw and wood chips) slurry flows.
Sand- and biomass-water mixtures were prepared over a wide range of concentrations (1.5–20 wt%, dry) and pumped over a range of velocities (0.04–4.5 m/s) much wider than the common industrial practice of 1.4–3.0 m/s. Besides the impedanceometry device, the LCR meter was used to measure the slurry flow deposition velocity to validate accuracy and reliability of the impedanceometry setup circuit. On a graph of impedance-velocity, the velocity corresponding to the point of inflection was reported the deposition velocity. The deposition velocities measured for sand-water mixture flows were compared with those calculated using previously reported empirical correlations where a deviation as small as 7.0% was found. In addition, it was proved that deposition velocities in biomass-water mixtures are well below common industrial pumping velocities, i.e., particle deposition is not an issue in biomass pipelines. The high-frequency impedanceometry approach was found to be a replacement for traditional techniques such as gamma ray densitometry, visual observations, and ERT systems, since it does not disturb/stop the slurry flow and is simple and economic to fabricate, easy to operate, easy to mount on the pipeline, applicable to all the suspensions conducting electricity, and capable of accurately measuring slurry deposition velocities as low as 0.04 m/s.

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