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The effect of nanocrystalline cellulose on flow properties of fiber crop aqueous suspension

Samira Gharehkhani[a,b,*], Seyed Farid Seyed Shirazi[c,d], Hooman Yarmand[e], Elham Montazer[d], Salim Newaz Kazi[d,**], Rushdan Ibrahim[f], Mehdi Ashjaei[b], Nurin Wahidah Binti Mohd Zulkifli[e], Sadegh Rahmati[c]

[a] *Chemical Engineering Department, Lakehead University, 955 Oliver Road, Thunder Bay, Ontario, Canada*
[b] *Department of Mechanical Engineering, University of Tehran, Tehran, Iran*
[c] *Department of Mechanical and Aerospace Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran*
[d] *Department of Mechanical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia*
[e] *Centre for Energy Sciences, Department of Mechanical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia*
[f] *Forest Research Institute Malaysia, 52109 Kepong, Selangor, Malaysia*

A R T I C L E I N F O

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A B S T R A C T

Nanocrystalline cellulose (NCC) a nature-based material, has gained significant attentions for its unique properties. The present study aims to investigate the flow behavior of cellulosic suspension containing non-wood pulp fibers and NCC, by means of rheological and pressure drop measurements. The NCC sample was prepared by sulfuric acid hydrolysis from Acacia mangium fibers. The rheological properties of kenaf/NCC suspensions were studied using viscosity and yield stress measurements. The pressure drop properties of the suspension flow were studied with respect to variation in flow velocity (0.4 m/s–3.6 m/s) and the NCC concentration (70 mg/l and 150 mg/l). The pressure drop results showed that the pulp suspension containing 150 mg/l NCC had higher drag reduction than kenaf suspension alone. The present insights into the flow of pulp/NCC suspension provide a new data and promote the application of NCC in industries.

1. Introduction

Understanding of the flow behavior of pulp suspension could be used to proper design of various manufacturing plants such as food, composites, textiles, membrane, and pulp and paper (Heydarifard, Pan, Xiao, Nazhad, & Shipin, 2017; Kazi, Duffy, & Chen, 2015). Numerous studies have been conducted to study the pulp flow characteristics and generate data for pressure drop of pulp suspensions. Duffy (1972) has outlined various regimes of flow phenomena for chemically cooked pulps in terms of head loss-velocity curve. The flow behavior in pipe flow can be divided in three different regimes (see Fig. 1): plug (region A–B), mixed (region B–C), and turbulent (region C–D). From a practical standpoint, the comparisons between the suspension pressure drop data and the ones obtained from water runs provide useful information. In comparison to the pressure drop curve for water, a reduction in pressure drop of wood pulp fiber suspension has been reported, where the phenomenon is termed "drag reduction" (Duffy, 1972; Kazi, Duffy, & Chen, 1999). Drag reduction is an engineering intervention to reduce turbulence in a pipe, and as a consequence, the cost. Drag reduction percentage is defined as $[1-\left(\frac{\left(\frac{\Delta P}{L}\right)_{fluid-additive}}{\left(\frac{\Delta P}{L}\right)_{fluid}}\right)]\times 100$. Momentum transfer and damping mechanism are affected by the type of suspension particles in the flow which also controls the level of drag reduction.

It is widely known that various parameters cause significant changes in the flow mechanism and rheological properties of pulp suspension. Until now, numerous studies regarding the effect of for example, fiber chemical treatment (bleaching), fiber length, fiber species and presence of additives (e.g. polymers and fines) on the flow behavior of the pulp suspension have been reported (Kamel & Shah, 2009; Kazi et al., 2015; Luettgen, Lindsay, & Stratton, 1991). Ventura, GarCia, Ferreira, & Rasteiro (2008) investigated the flow dynamics characteristics of four different fibers (recycled pulp, eucalypt bleached kraft pulp, pine unbleached kraft pulp, and eucalypt (90%) + pine (10%) bleached kraft pulp) and stated that the pulp flow is affected by the type of fibers. Recently, the fibers from non-wood sources, such as crops, agriculture residues, grasses and tree leaves which do not have immediate

* Corresponding author at: Chemical Engineering Department, Lakehead University, 955 Oliver Road, Thunder Bay, Ontario, Canada.
** Corresponding author.
E-mail addresses: sgharehk@lakeheadu.ca (S. Gharehkhani), salimnewaz@um.edu.my (S.N. Kazi).

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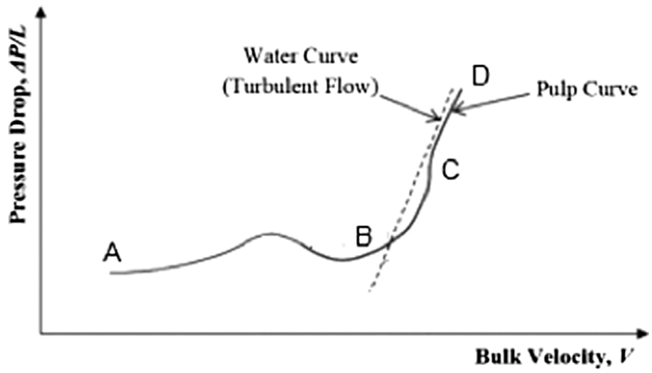

Fig. 1. Typical friction loss curves for pulp suspension.

beneficial applications in many communities have been proposed to be potential sources of pulp. In many Southeast Asian countries such as India, China, and Thailand, non-wood plants have become a major source of fiber. Among those, kenaf (*Hibiscus cannabinus* L.), as a fiber crop, attracted many interests as an alternative source for wood fibers in different fields, e.g., paper industry, building materials and composites, due to its low cost, reinforcement properties, biodegradability, and recyclability (Ochi, 2008; Yusoff, Takagi, & Nakagaito, 2016; Zainuddin, Ahmad, Kargarzadeh, Abdullah, & Dufresne, 2013). Gharehkhani et al. (2017) studied the momentum characteristics of kenaf pulp suspension in pipe flow. Kenaf suspension at the concentration of 0.6% (w/w) showed maximum drag reduction among the other two concentrations (0.2% and 0.4% (w/w)).

It has been stated that a polymer solution flowing in a pipe requires a lower pressure gradient to maintain the same flow rate (Kim, Kim, Lim, Chen, & Chun, 2009). Since the interaction between eddies and pipe wall leads to friction and pressure drop of the flow, adding a small concentration of such additives to the fluid reduces the friction of the fluid and increases the flow capacity of the pipeline (Karami & Mowla, 2012). Kamel and Shah (2009) used 2% KCl brine and synthetic sea water to investigate the effect of salinity on drag reduction of ASP-700 and ASP-820. Moreover, to study the effect of temperature, they conducted a set of tests at temperatures of 22.2, 37.7, and 54.4 °C and observed the drag reduction in the range of 30–80% by using the mentioned polymers. MacKenzie, Martinez, and Olson (2014) studied the influence of softwood kraft pulp fibers and synthetic polymer additives, e.g., cationic polyacrylamide (CPAM) and anionic polyacrylamide (APAM) as the most widely used retention aid products in the papermaking, on turbulent drag reduction in a hydrocyclone. They reported a slight increase in drag reduction with an increase in polymer concentration from 100 to 500 mg/l of APAM/CPAM.

Apart from the conventional additives, a series of new additives are coming into account in industries, and nanocellulose is one of them. Nanocellulose can be produced in forms of nanofibrillated and nanocrystalline (Afra, Yousefi, Hadilam, & Nishino, 2013). The low cost of the nanocellulose raw sources along with its renewability, high surface area and high specific strength made it one of the most attractive renewable materials. Numerous studies have conducted on the application of nanofibrillated cellulose (NFC) and nanocrystalline cellulose (NCC) in order to tailor the mechanical properties of final products (Brodin, Gregersen, & Syverud, 2014; Kajanto & Kosonen, 2012; Li, Mascheroni, & Piergiovanni, 2015). For examples, several research studies have shown that NFC can be used as a dry strength additive (Balea et al., 2016; González et al., 2012; Kajanto & Kosonen, 2012; Sehaqui, Zhou, & Berglund, 2013; Vallejos et al., 2016). Balea et al. (2016) used the NFC to enhance the tensile index of the recycled papers. To reduce the drawbacks on the drainage, addition of an optimal dosage of NFC along with the suitable retention system could be suggested.

To produce NCC, the crystalline region of cellulose is extracted by using acid hydrolysis method that would result in a stable suspension containing rod-shaped NCC (Rånby, 1951). A commonly used method to make NCCs is hydrolysis process using sulfuric acid, which introduces anionic sulfur ester groups on surfaces and makes the suspension stable (Brinchi, Cotana, Fortunati, & Kenny, 2013; Huang, Liu, Sun, & Fatehi, 2016; Shafiei Sabet, 2013). In April 2015, API started up a 100 ton per year plant at its biorefinery in Thomaston GA and CelluForce produces 1000 kg/day of NCC (Miller, 2014; Miller, 2017).

Recently, there is a great interest in utilizing NCC to increase the strength and quality of composites (Nagalakshmaiah, Mortha, & Dufresne, 2016; Shahabi-Ghahfarrokhi, Khodaiyan, Mousavi, & Yousefi, 2015; Xu et al., 2013). Xu et al. (2013) have isolated NCC from bleached aspen kraft pulp and used it as an additive in deinked pulp. They reported that NCC can be used for improving the strength properties (breaking length and tear index) of papers. The strength properties of hand sheets were improved due to the presence of NCC in the fiber suspension which has increased the hydrogen bonding between the fibers. Therefore, the effect of NCC as a strength additive is expected to be more significant dealing with the poor bonded sheets of the mechanical pulps or recycled pulps (Balea et al., 2016; Brodin et al., 2014). The oxidized NCC prepared using the sodium periodate was also reported to use as a strength additive for paper where both dry and wet tensile indexes were increased (Sun, Hou, Liu, & Ni, 2015). NCC could be used in microparticle retention systems as organic anionic particle due to its nano range diameter and surface charge density. Since using nanocellulose in industry is going to be applicable, study on the flow of pulp/nanocellulose suspension in the pipeline is inevitable. According to an invention, NFC can be used to dampen the turbulence in papermaking (Maclachlan, Shopsowitz, Hamad, & Qi, 2014). However, in case of NCC, the studies are limited to the rheological properties. Shafiei-Sabet, Hamad, and Hatzikiriakos (2012) performed an extensive work on the rheological properties of NCC suspension. Their results demonstrated that the suspension up to 3% (w/w) showed isotropic phase. Additionally, the NCC samples with higher concentrations showed anisotropic phase with fingerprint texture and liquid crystal behavior. Further increase in the concentration resulted in a gel form of NCC (Lu, Hemraz, Khalili, & Boluk, 2014). Gonzalez-Labrada and Gray (2012) measured the viscosity of dilute aqueous suspensions of cellulose nanocrystals by using a rolling ball viscometer and evaluated the non-Newtonian character of NCC suspensions at increased concentrations. Although, various studies were performed on the rheological properties of NCC suspensions, to the best of authors' knowledge there is not any report regarding the pressure loss data of pulp suspension containing NCC in the pipe flow. The present study aims to investigate the effect of NCC on the pressure loss characteristic of pulp suspension flow.

2. Methodology

2.1. Pulp suspension preparation

Kenaf (two stages of soda) in lap form provided by the Forest Research Institute Malaysia (FRIM) was used in the present study. Fiber length, fiber width and lumen diameter were measured based on an average of 50 measurements by using a Quantimeter Image Analyzer equipped with a Lecia microscope and Hipad digitizer (from Quantimet 520, Cambridge Instruments). The length, width and lumen size of fiber were 2320 μm, 40.8 μm and 24.6 μm with standard deviations of 280.0 μm, 14.3 μm, and 9.1 μm respectively.

To prepare the pulp suspension with concentration of 0.6% (w/w), the required amount of the sample calculated based on the moisture content was soaked in water for 24 h. The soaking process was necessary before disintegration to rehydrate and disperse the samples. Then the fiber suspension sample was divided to small portions with 1.2% (w/v) consistency and disintegrated at 3000 rpm until all fiber bundles were dispersed. The disintegration process was done according to