International Communications in Heat and Mass Transfer 80 (2017) 60–69

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Experimental investigation on rheological, momentum and heat transfer characteristics of flowing fiber crop suspensions

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ARTICLE INFO

Available online 13 December 2016

Keywords:
Pulp suspension
Viscosity
Heat transfer
Pressure drop
Drag reduction

ABSTRACT

The study of pulp suspension flow is one of the most significant scientific interests since the considerable changes in the flow behavior of water were noticed after adding a small amount of fiber to water. The rheological studies on Kenaf pulp (a fiber crop) suspensions revealed that concentration has a great influence on variations of viscosity and yielded stress values. Heat transfer and pressure loss data were obtained from Kenaf suspension flow at different concentrations over a wide velocity range in a straight pipe. Kenaf suspension at the concentration of 0.6 wt.% showed maximum drag reduction. A considerable increase in the heat transfer coefficient of Kenaf suspension (0.2 wt.%) was also observed. Such an increment in the heat transfer coefficient ratio of Kenaf suspension flow is interesting since the enhancement of heat transfer has mostly been reported for suspensions containing nanoparticles and not for natural fibers in microscale. Moreover, the effects of fiber length and flexibility on momentum and heat transfer data were studied.

1. Introduction

The flow of fiber suspensions has been applied in many industries, such as reinforcing composites, food processing, textiles, pulp, and the paper industry. Pulp and paper industries are the biggest users of fiber suspension. The major raw material in paper-making is pulp, which consists of cellulose fibers that come from wood and non-wood plants. The main sources for wood pulps are softwood trees (e.g., spruce and pine) and hardwood trees (e.g., eucalyptus and aspen). Concerning non-wood, crops and agriculture residues are used (e.g., empty fruit bunch and Kenaf) [1–3]. Presently, due to the rising global demand for fibrous material, the shortage of trees in many areas, and increasing environmental awareness, fiber crops have become one of the most important alternative sources of fibrous material in the 21st century [4]. One of the fiber crops used as a source for paper-making is Kenaf (*Hibiscus cannabinus* L.) Southern Asian countries such as India, China, and Thailand account for 90% of the world's plantations and more than 95% of the world's production of Kenaf [5].

An understanding of pulp suspension's flow behavior can be used to design pipelines in the paper industry, which may curb the rejected paper production. From the standpoint of flow behavior studies, knowledge of the rheological properties of suspensions is essential. There are many studies on the viscosity variations of suspensions containing solid particles in both nanoscales and microscales [6,7]. Fibers in water change the water's rheological behavior. The interactions between the fibers and the hydrodynamic disturbance to the flow field result in increased viscosity. There have been a few studies on the rheological properties of very dilute pulp suspensions

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2016.11.013
0735-1933/

Nomenclature

A	Area, m^2
C	Concentration, %
D	Inner diameter of the tube, m
f	Friction factor
h	Heat transfer coefficient, KW/m^2 K
I	Current, Amp
k	Thermal conductivity, W/m K
l	Length of the tube, m
Nu	Nusselt number,
P	Power, Watts
Pr	Prandtl number
$\dot{q}$	Heat flux, W/m^2
Re	Reynolds number,
T	Temperature, °C
u	Velocity, m/s
x	Distance of thermocouple from the inner surface of pipe.

Greek symbols

Δp	Pressure drop
λ	Wall thermal conductivity
μ	Viscosity, kg/m^2 s
ρ	Density, kg/m^3
τ	Shear stress

Subscripts

b	Bulk
i	Inlet
m	Mass
o	Outlet
t	Thermocouple
w	Wall

[8–10]. Chen et al. [9] studied the rheological properties of very dilute pulp suspensions at a wide range of shear rates and at different mixture ratios of softwood and hardwood kraft pulp fibers. They observed an unstable flow in the middle range of shear rates and Newtonian flow regimes at very low shear rates as well as at high shear rate values. Yield stress is one of the most important rheological properties of fiber suspensions [10]. It is defined as the minimum stress required to overcome the network stress of the suspension for generating the initial flow. The yield stress has been applied in various fields, such as pulp pipe flow as well as pulp mixing operations [11]. Derakhshandeh et al. [10] used a rheometer with vane geometry. It is known that a vane rotor with at least 4 blades and a large cup would minimize the slip effects of measuring the rheological properties of pulp suspensions.

Apart from the rheological properties, heat transfer and pressure loss data are used to investigate solid-liquid mixture flow behavior [12,13]. Few studies have been conducted on the flow of non-wood pulp suspensions, where data on the pressure drop of rice straw, bagasse, and wheat straw pulp suspensions at low concentrations and flow velocities up to 2.5 m/s were generated [14]. The earliest work on flow regimes was presented by Duffy [15], who outlined various regimes for chemically cooked pulps in terms of head loss-velocity curve. Pipe flow behavior can be divided into three different regimes: plug, mixed, and turbulent. Jäsberg [16] conducted some new experiments to obtain more details about the flow behavior of chemically released pine or birch pulps at the consistency of 0.52 0% by weight in a pipe diameter of 40 mm. In comparison to the pressure drop curve of water, a reduction in the pressure drop of wood pulp fiber suspension has been reported, where the phenomenon is termed "drag reduction" [15,17,18]. Drag reduction is an engineering intervention used to decrease the cost of pumping to transport fluid over long distances. Drag reduction percentage is defined as $[1-(\frac{(\frac{\Delta P}{L})_{fluid-additive}}{(\frac{\Delta P}{L})_{fluid}})]\times 100$. Momentum transfer and damping mechanism are affected by the type of particles in the flow, which also controls the level of drag reduction. The types of particles have been referred using the categories introduced by Duffy [19]. At low concentrations, fibers act as individual particles that can become entangled to form floccettes and flocs with slightly increased pulp concentrations. Interlocking the fibers at higher concentrations forms a network of fibers. The networks appear at low flow velocities where there are plug flow regimes. As the velocity increases, the transition region appears for all types of particles. In the transition flow regime, the momentum transfer is enhanced by the interlocking of fibers, which forms a solid continuum. However, fibers and flocs dampen turbulent eddies, which tends to reduce the effective momentum transfer. Momentum transfer enhancement, therefore, predominates suspension behavior at low flow rates, and the fiber-damping mechanism controls that at higher velocities [17].

Unlike the diversity in pressure drop studies, there is little data on heat transfer to pulp suspension. In a pioneering study, Middis [20] reported a reduction in the heat transfer coefficient (h_c) of fiber suspension in comparison to the water, which was caused by the development of a thin shear layer between the pipe wall and the fiber plug network (interlocking fibers) where the pulp concentration was more than 2 wt.%. Kazi and coworkers [17] conducted experiments in low concentrations (<0.4 wt.%) of wood pulp and found an increase in h_c with an increase in velocity. In subsequent studies, Duffy, Kazi and Chen [18,21] showed that h_c depends on fiber properties. As a result of these studies, Kazi and Duffy [21] correlated h_c to fiber and paper properties from wood sources.

Non-wood fiber suspension flow properties have not been explored as is the case for wood pulp fiber suspensions. Thus, there are extensive requirements for a detailed study on the heat transfer and friction loss characteristics of non-wood fiber suspensions. With this said, the aim of the present work was to generate data on the pressure loss and h_c of a fiber crop suspension.

2. Experimental apparatus and procedure

2.1. Pulp suspension preparation

Pulp fiber suspensions were provided by the Forest Research Institute Malaysia (FRIM) and prepared from 2 stages of soda Kenaf in lap form. The suspension was disintegrated at 3000 rpm until all the fiber bundles dispersed. After disintegration, the pulp suspension was added to a 100 L tank and dispersed homogeneously by an agitator. The concentration of the slurry was adjusted to 0.2, 0.4, and 0.6 wt.%. Regarding the beating process, the Kenaf fibers were beaten by the PFI mill-refining machine with 2 beating degrees of 2000 and 4000.

2.2. Pulp characterization

For this study, fiber length (L), fiber width (W), and lumen diameter (d) were measured based on an average of 50 measurements using a Quantimeterimage analyzer equipped with a Lecia microscope and Hipad digitizer (from Quantimet 520, Cambridge Instruments). Fiber flexibility ($100 \times d/W$) was calculated using the measured data [22]. The microscopic images of fibers were taken using the scanning electron microscope (SEM) at a magnification of 500×.

2.3. Shear viscosity measurement

The rheological measurements were performed using a hybrid rheometer (TA instrument) with a vane concentric cylinder's geometry