

Experimental investigation on momentum and drag reduction of Malaysian crop suspensions in closed conduit flow

S M Ahmed^{1*}, S N Kazi^{1*}, G Khan¹, M Dahari², M N M Zubir¹, P Ahmad³, E Montazer¹.

¹ Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia.

² Department of Electrical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

³ Department of Physics, Faculty of Science University of Malaya, 50603 Kuala Lumpur, Malaysia.

E-mail: *syed.ma@hotmail.com

Abstract. The study of frictional losses in fiber suspension flow is one of the significant scientific interests as the characteristics of suspension flow considerably changes with shear stress, fiber source, and treatments applied on fibers. Pressure drop measurements were obtained for different Malaysian crop fiber suspensions flowing through a closed conduit. The generated data were gathered over a range of flow rates and suspension concentrations. It was found that the magnitude of the pressure drop of the fiber suspensions is dependent on the concentration, characteristics, and fiber source. Considerable drag reduction is obtained for concentration of 0.6 wt. % at high flow rates. Such a reduction of pressure drop at the particular concentrations and the flow rates is interesting and useful as these data can be used for design and optimization of fiber handling equipment and piping systems. Furthermore, the effect of different fibers, fiber properties and flexibility on pressure drop were studied.

1. Introduction

Fiber suspension flow is different from Two-phase flow occurs in the transportation of oil and gas, mining, petrochemical process, boilers and condensers as fibers are flexible and asymmetric. Usually fibers suspensions flows are occurring in many applications, such as pulp and paper, textile, fiber composites etc. Studies conducted on fiber suspensions flow and their characterization and correlations are mainly wood pulp fibers. The physical characteristics of the fiber suspensions, as well as the properties of the end products, are dependent on the hydrodynamic behavior and structure of the suspensions [3]. Features, such as consistency, flow conditions, interactions and fiber properties affect the hydrodynamic behavior and structure of the suspensions flow. The investigations conducted on fiber suspensions flow and characterization of fiber suspensions are mainly wood pulps and polymeric fibers [4-8].

Due to increasing demand for fibrous materials, limitation of the wood source and environmental concern, the study of non-wood fibers suspensions has become imminent. Crops based fibers attracting the focus of pulp and paper industry as well as researchers, as it is recognized as an alternative source of wood fibers. Kenaf, crop-based fiber reported as an alternative source of wood for the pulp and paper production that have two distinctive stem regions, the outer portion or Bast is



about 34 wt.% of the stem and inner, woody core, that is about 66 wt.% [9]. Kenaf bast fiber resembles long softwood fibers which could be used for high-grade pulps production [10-12].

Understanding, the hydrodynamic behavior of pulp suspensions and its correlation with fiber properties, flow conditions and consistency can therefore act as an aid in the design and optimization of processes and products. Kazi, Duffy and Chen [13] have studied drag reduction of wood pulp fiber at different consistencies over a range of flow rates in a pipe. They observed that small amount of fiber in suspension reduces pressure losses than that of water. Duffy, Kazi and Chen [5] considered the findings [13] and correlated the pressure drop with fibers and paper properties. They reported that little modification in fiber properties could be sensed by some little changes in pressure drop at low consistency. They also reported that pressure drop measurements could be correlated and utilized for the prediction of specific fiber and paper properties and these measurements could be significant for retardation of production of low quality or reject papers. Duffy, Kazi and Chen [4] studied pressure drop characteristics of wood (Kraft pine pulps, a spruce pulp, and a eucalypt) pulp fibers and synthetic model polymer fibers and compared with the pipeline studies. They reported the effect of fiber concentrations on pressure drop. The correlation between concentration and fiber properties were generally well versed and they highlighted fiber stiffness and fiber population as key variables. Frictional pressure drop decreases with the increase of fluid velocity, fiber flexibility, and an increase of consistency. Frictional pressure drop was also affected by varying fiber properties, such as fiber length, fiber flexibility, fiber mechanical and chemical treatment as well as different pulping methods used for pulping, furthermore frictional pressure drop can be used to adjust the degree of fiber refining treatment so that the paper made from those fibers are within the product specifications [14, 15].

Crop pulp fiber suspensions flow and their correlation with fiber properties have not been explored as in the case of wood pulp fiber suspensions. Thus, there are extensive requirements for a detailed study of crops pulp fibers on frictional losses and their correlations with fiber properties. The aim of the present work is to generate experimental frictional loss data and their correlation with fiber properties for different crop pulp fibers and their blends for future development of valid models of turbulent fiber suspensions flow and to introduce insight on the advancement of fiber processing, design and optimization of process and product by characterization of the hydrodynamic behavior of fiber suspensions.

2. Experimental

2.1 Material

Kenaf bast and Kenaf core pulp fiber samples were prepared by the mechanical process (refining mechanical pulping RMP) (kbn and kcm). The blend kckb3 of Kenaf core and Kenaf Bast pulps were prepared by mixing Kenaf core and Kenaf bast pulp with a ratio of 9:1. Pulp samples used in the investigation were provided by Forest Research Institute of Malaysia (FRIM).

2.2 Experimental set-up

Flow loop of the test section and the equipment used are presented in this section. A schematic diagram of the experimental setup is shown in Figure 1. The flow loop of the test rig consists of stainless steel piping, jacketed stock tank connected with a chiller for cooling of pulp suspensions at the desired bulk temperature, a variable speed pump, a magnetic flow meter, a differential pressure transducer, heated test section and the recycle pipings. A differential pressure transducer (IDP10 FOXBORO) was used to measure the frictional losses across the test section. Ten flat coil heaters, 900 W each were utilized for the heating of the test section. The pulp suspension was pumped from the 100 L capacity stainless steel tank by the LOWARA stock pump driven by a 2.71 KW AC motor which was controlled by a Hoffman Muller™ inverter.

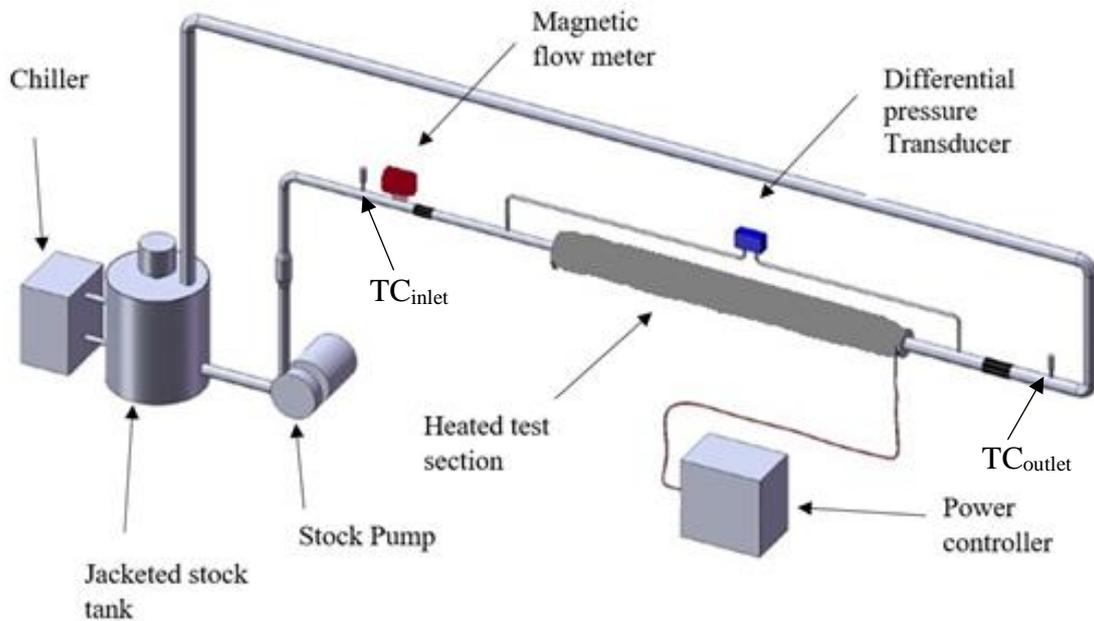


Figure 1. Schematic diagram of experimental setup.

2.3 Data acquisition

The inlet temperature data were logged using a data logger (Graphtec, midi logger GL220). The flow rate was measured by using Magnetic flow meter 8000 A SERIES (FOXBORO) and a Differential Pressure cell transmitter IDP10 (FOXBORO) was used to measure the pressure drop. The heater power was adjusted to 3.3 kW by manipulating current and voltage supplied to the heater in order to maintain constant inlet temperature, and the supplied current and voltage data were measured by 1000 A true RMS meter (Agilent). All the data were taken at steady-state conditions at an instantaneous velocity, bulk temperature, and heat flux.

The Moody friction factor (f_M) is calculated by Eq. (3) using the measured data of bulk velocity (u), Pressure drop (ΔP), pipe diameter (D), pipe length (L) and suspension density (ρ).

$$f_M = \frac{D}{L} \frac{\Delta P}{\frac{1}{2} \rho u^2} \quad (1)$$

The correlations of Petukhov (f_p) [1] and the Blasius relation [2] are presented in equation (2) (3) respectively.

$$f_p = (0.79 \ln Re - 1.64)^{-2} \quad 4000 < Re < 5 \times 10^6 \quad (2)$$

$$f = 4 \times \frac{0.0791}{Re^{0.25}} \quad (3)$$

2.4 Experimental procedures

The pulp fibers were disintegrated in the disintegrator up to 35000 rpm before conducting each experiment. The disintegration process was carried out according to the TAPPI standard where the revolutions were not more than 50,000 (TAPPI, 2002). Then pulp suspensions were prepared in the stock tank, stirred for 1 hour then pumped through the loop for approximately two hours to ensure

homogeneous fiber dispersion before any set of data were taken. Once steady state conditions were achieved and inlet temperature maintained at 32°C then pressure drop data were taken in a range of velocity (0.4-2.8 m/s).

3. Results and discussion

3.1 Data Reproducibility and Test rig calibration

To validate the new experimental data, a preliminary set of test were conducted keeping the water as a working fluid. The measured Pressure drop for the new experimental data was correlated with the Petukhov [1] and Blasius [2] correlations and presented in figure 2. It revealed that the measured experimental data are in good agreement with the evaluated values from the empirical correlations and it is observed that with an increase of velocity the deviation between experimental and correlations decreases. In particular, Petukhov [1] empirical correlation are within the agreement of about 7% with the experimental data and Blasius relation [2] are also in good agreement of about 8% with the experimental data, that validates the experimental methodology.

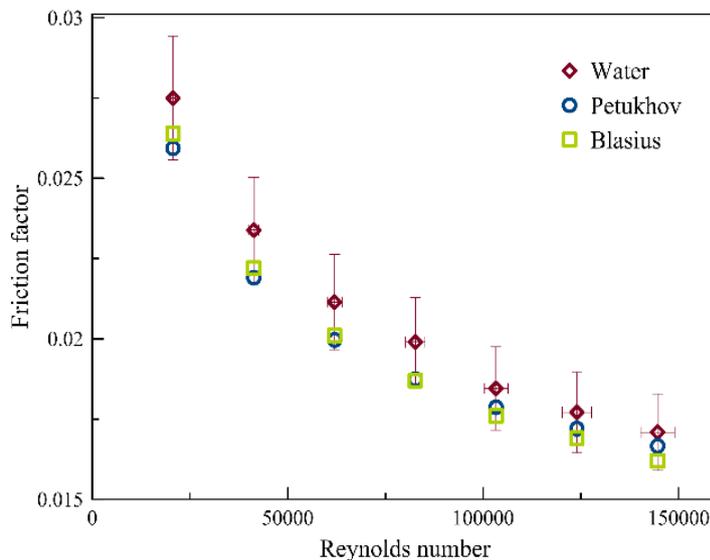


Figure 2. Comparison of the measured experimental friction factor with the Petukhov [1] and the Blasius [2] correlations.

3.2 Concentration effect of fiber on pressure drop

Effect of fiber concentration on drag reduction was studied using kckb3 pulp. Figure 3 presents the ratio of the pressure drop of suspensions and pressure drop of water as the function of velocity for water and kckb3 at different concentrations (0.2, 0.4, and 0.6 wt.%) and a constant inlet temperature of 32 °C and constant heat flux of 23.2 KW/m². It is observed that at the lowest velocity 0.4 m/s the drag ratios of suspensions are sufficiently higher than that of water, whereas at the highest concentration of 0.6 wt.% have shown the highest drag ratio. Higher drag ratio at low velocity, substantially owing to the presence of a plug where the turbulent sheared layer between the plug and the pipe wall is very thin and the velocity profile is steep [13]. The drag reduction is not achieved throughout the range of velocity (0.4 – 2.8 m/s) for all consistencies of pulp suspensions. The subsequent decrease in drag ratio with an increase of flow is owing to the dominance of fiber damping the turbulence. It is observed that the magnitude of drag ratio decreases with the increase of velocity and consistency. The minimum drag ratio is observed for highest concentration of 0.6 wt.% at 2.8 m/s and that is slightly higher than the pressure drop of water

3.3 Effect of different fibers on suspension properties

To study the effect fiber source on frictional pressure drop, the blend kckb3 (a mixture of kcm and kbm with mass ratio 9:1) pulp suspension were compared with primary pulp fibers kcm and kbm at a range of velocity 0.4-2.8 m/s and with a concentration of 0.6 wt.% and constant inlet bulk temperature of 32°C along with water presented in figure 4 as a drag ratio. At low velocity of 0.4 m/s, adequate distinction is observed in the drag ratio values of kcm, kbm and kckb3 whereas the the enormous difference between pulp suspensions and water values is marked. Furthermore, kbm showed the highest drag ratio 1.512 followed by kckb3 1.279 and kcm 1.217. The blend increased the drag ratio about 5.09% than that of kcm (the primary pulp in the blend) at a low velocity of 0.4 m/s. High drag

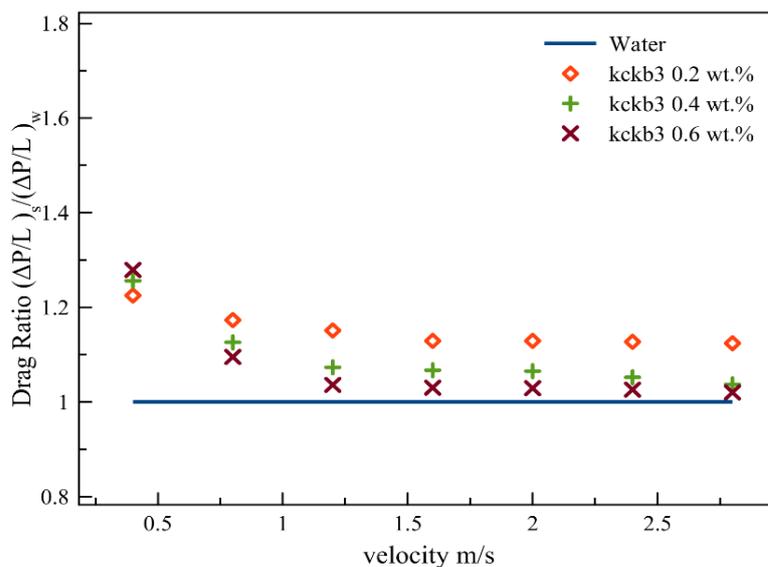


Figure 3. Drag ratio as a function of flow velocity for water and kckb3 pulp suspension at different concentrations.

ratio at low velocity, substantially due to the presence of a plug where the turbulent sheared layer between the plug and pipe wall is very thin and the velocity profile steep. The highest drag ratio marked by kbm at low velocity 0.4 m/s is due to heist aspect ratio that interacts with neighboring eddies, deflect, bend and absorb turbulent energy.

The minimum drag ratios 0.966, 1.02 and 1.035 are observed for kbm, kckb3 and kcm at velocity 1.6, 2.8 and 2.8 respectively. These results indicate that floc and network formation even at same concentration occur at different velocities and in the case of long fiber (kbm) the minimum drag ratio is observed in the mid-range of velocity 1.6 m/s over this point drag ratio successively increases slightly. While short fiber (kcm) and kckb3 showed a successive decrease in drag ratio until the maximum velocity 2.8 m/s investigated in the present study. Whereas, addition (blending) of 10 wt.% long fiber (kbm) in short fiber (kcm) decreased pressure drop about 1.45% than that of kcm.

To magnify the phenomenon of deflecting, bend and absorbing turbulent energy or aid in transmitting momentum with aspect ratio, the blend kckb3 were prepared by mixing pulp fibers with high aspect ratio 146.58 (kbm) with low aspect ratio 25.45 (kcm). The results reveal that with the increase of aspect ratio of fibers in suspension pressure drop decreases. Furthermore, consequent decrease in pressure drop with an increase of velocity is owing to the dominance of shear stress and formation of flocs and network that have special plastic-elastic characteristics

3.4 Fiber characterization

Fiber physical properties could modify turbulent eddies that affect frictional pressure drop. Due to practical and economic reasons, papermaking technologists are interested in flocculation [16]. Flocculation effect paper strength, uniformity, appearance [17-19] and adversely affect subsequent operations, such as coating [20]. Flocculation and consequently the frictional pressured drop would be

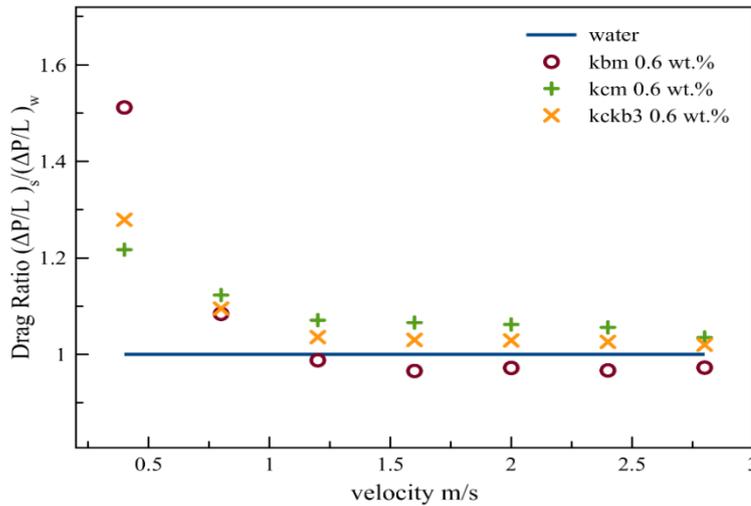


Figure 4. Frictional pressure drop (a,) and Drag ratio (b) as a function of flow velocity for water and different pulp suspensions kbm, kcm and kckb3 at concentration of 0.6 wt.%.

affect by any deviation in fiber properties particularly fiber length and flexibility. Also, many researchers [14, 21] reported that fiber flexibility is dependent on cross-dimensional fiber properties and increases with the decrease of fiber cell wall thickness. Some fiber characteristics could be analyzed by pressure drop measurements [15, 22]. Considering those previous studies which were based on wood and synthetic fibers, there was a need to evaluate pressure drop measurements over a range of flow conditions for crop pulp fibers. To correlate pressure drop of flowing crop pulp suspensions with the fiber length, fiber lumen, and fiber width (other properties are presented in appendix), the consistency of 0.6 wt.% and the velocity of 1.6 m/s were selected in the present study as shown in the Figures 6 (a – c).

The results reveal that the pressure drop could be used for monitoring deviations in fiber characteristics and hence pulp and paper quality. The deviations in pressure drop between kcm, kbm

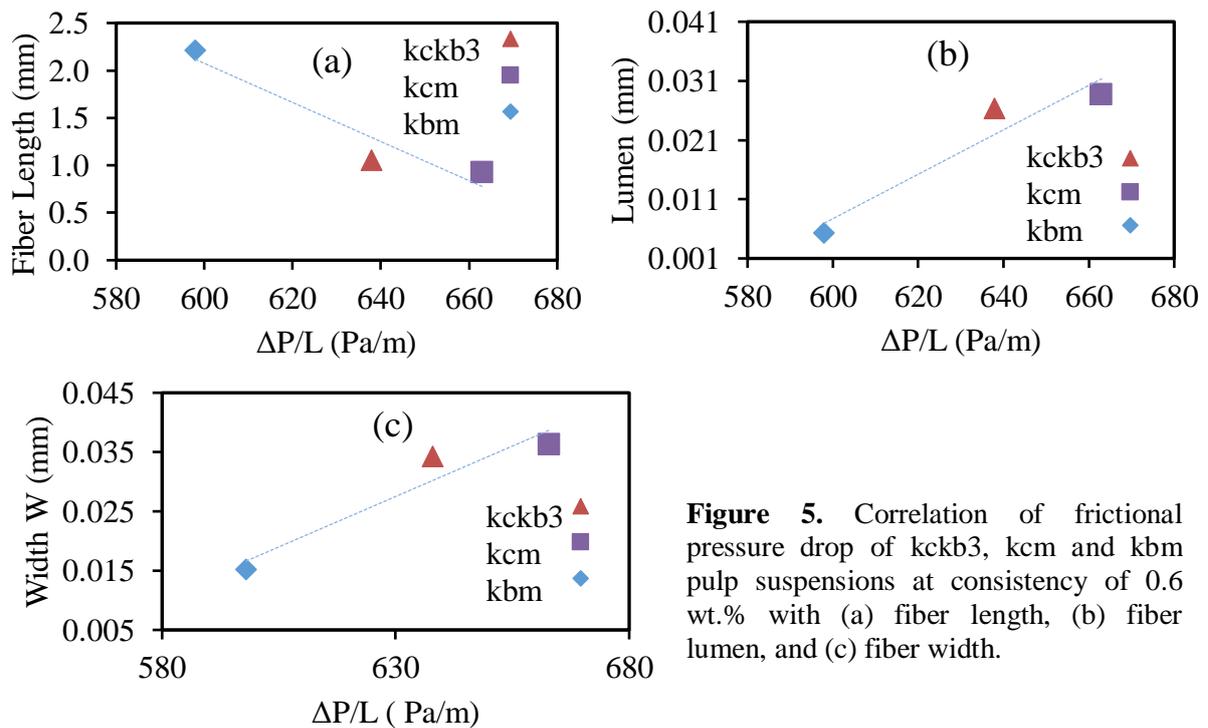


Figure 5. Correlation of frictional pressure drop of kckb3, kcm and kbm pulp suspensions at consistency of 0.6 wt.% with (a) fiber length, (b) fiber lumen, and (c) fiber width.

and kckb3 pulp suspensions are due to fiber flexibility and lignin content and aspect ratios. The findings and data trends are similar with the previous researchers for wood pulp and synthetic fibers [4, 13, 22-24].

4. Conclusions

Suspensions of wood and synthetic fibers flow, properties of different grades of fibers and their correlation with frictional pressure drop have been studied by many researchers. In the present study momentum transfer of fiber suspensions of a different crop pulp fibers (kenaf core and kenaf bast) and their blend has been considered. The fiber consistency, flexibility, aspect ratio of pulp fibers suspensions influence frictional pressure drop, while among these features fiber consistency is an important parameter. It is concluded that with the increase of the concentration of the suspensions, frictional pressure drop reduces at higher flow rates, and drag reduction is observed at a concentration of 0.6 wt. % for kbm pulp suspension. The minimum drag ratio occurs at different flow velocities depending on pulp samples. The drag ratio slightly increases with velocity after the minimum drag ratio point in case of long fibers. Contrarily, drag ratio is successively decreasing with the increase of velocity. The flexible fibers reduces pressure drop by dampening more eddies in comparison to the stiff fibers and hence enhances drag ratio. The results acquired in the present study can elucidate the handling of crop fibers in pulp and paper industries.

Acknowledgements

This research has been financially supported by High Impact Research (MOHE-HIR) grant UM. C/625/1/HIR/MOHE/ENG/45, UMRG-RP012C-13AET, Bantuan kecil penyelidikan BK 009-2016, Faculty of Engineering, University of Malaya and the authors are also grateful to the Forest Research Institute of Malaysia for support to conduct this research work.

References

- [1] Petukhov B 1970 *Advances in heat transfer* **6** 503-64
- [2] Blasius H 1908 2. *angew. Math*
- [3] Jayageeth C, Sharma V I and Singh A 2009 *International Journal of Multiphase Flow* **35** 261-9
- [4] Duffy G, Kazi S and Chen X 2011 *Applied Thermal Engineering* **31** 2971-80
- [5] Duffy G, Kazi M and Chen X 2002 *Proceedings of the 56th Annual Appita Conference, Rotorua, New Zealand*,
- [6] Duffy G G 1972 A study of the flow properties of New Zealand wood pulp suspensions.
- [7] Middis J, Muller-Steinhagen H and Duffy G 1994 *Appita* **47** 154-8
- [8] Cui H and Grace J R 2007 *International Journal of Multiphase Flow* **33** 921-34
- [9] Ashori A 2006 *Polymer-Plastics Technology and Engineering* **45** 1133-6
- [10] Villar J, Revilla E, Gómez N, Carbajo J and Simón J 2009 *Industrial crops and products* **29** 301-7
- [11] Dutt D, Upadhyay J, Singh B and Tyagi C 2009 *Industrial crops and products* **29** 16-26
- [12] Mossello A A, Harun J, Shamsi S R F, Resalati H, Tahir P M, Ibrahim R and Mohmamed A Z 2010 *Agricultural Journal* **5** 131-8
- [13] Kazi M S N, Duffy G G and Chen X D 1999 *Chemical Engineering Journal* **73** 247-53
- [14] Kazi S, Duffy G and Chen X 2014 *International Journal of Thermal Sciences* **79** 146-60
- [15] Kazi S, Duffy G and Chen X 2015 *Applied Thermal Engineering* **78** 172-84

- [16] Hubbe M A 2007 *BioResources* **2** 296-331
- [17] Rojas O J and Hubbe M A 2005 *Journal of dispersion science and technology* **25** 713-32
- [18] Korteoja M, Lukkarinen A, Kaski K and Niskanen K 1997 *Journal of pulp and paper science* **23** J18-J22
- [19] Korteoja M, Salminen L, Niskanen K and Alava M 1998 *Journal of pulp and paper science* **24** 1-7
- [20] Hua X, Tanguy P A, Li R and Van Wagner J S 1996 *appi journal* **79** 112-6
- [21] Paavilainen L 1993 *Paperi ja puu* **75** 689-702
- [22] Duffy G, Kazi S and Chen X 2000 *Proceedings of the 54th Annual Appita Conference, Melbourne, Australia, Apr*, pp 3-6
- [23] Kazi S, Duffy G and Chen X 2012 *Experimental Thermal and Fluid Science* **38** 210-22
- [24] Gharekhani S, Yarmand H, Goodarzi M S, Shirazi S F S, Amiri A, Zubir M N M, Solangi K, Ibrahim R, Kazi S N and Wongwises S 2017 *International Communications in Heat and Mass Transfer* **80** 60-9