Applied Thermal Engineering 78 (2015) 172–184

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Heat transfer coefficient of flowing wood pulp fibre suspensions to monitor fibre and paper quality

S.N. Kazi [a, *], G.G. Duffy [b, 1], X.D. Chen [c, 2]

[a] Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[b] Department of Chemical and Materials Engineering, School of Engineering, University of Auckland, Private Bag 92019, Auckland, New Zealand
[c] School of Chemical and Environmental Engineering, College of Chemistry, Chemical Engineering and Material Science, Soochow University, Suzhou Industrial Park, Jiangsu Province 215123, P.R. China

HIGHLIGHTS

- Heat transfer to natural fibre suspensions is governed by fibre properties and velocity.
- Heat transfers to fibre suspensions are affected by the fibre manufacturing methods.
- Heat transfers are affected by the degree of chemical and mechanical treatment of fibres.
- Heat transfer coefficient decreases with increasing of fibre flexibility.
- Heat transfer to fibre suspensions could be correlated with the fibre and paper properties.

ARTICLE INFO

Article history:
Received 12 May 2014
Accepted 8 November 2014
Available online 11 December 2014

Keywords:
Pressure drop
Heat transfer
Wood pulp fibre
Fibre concentration
Fibre flexibility

ABSTRACT

Heat transfer measurements were obtained for a range of suspensions of wood pulp fibre flowing through a pipeline. Data were generated over a selected range of flow rates and temperatures from a specially built flow loop. It was found that the magnitude of the heat transfer coefficient was above water at equivalent experimental conditions at very low fibre concentrations, but progressively decreased until it was below water at slightly higher concentrations. It was found that the heat transfer was affected by varying fibre properties, such as fibre length, fibre flexibility, fibre chemical and mechanical treatment, the variation of fibres from different parts of the tree as well as the different pulping methods used to liberate the fibres from the wood structure. Heat transfer coefficient was decreased with the increasing of fibre flexibility as found by previous workers. In the present investigation properties of fibre and paper are correlated with heat transfer to suspensions of fibres. Variations in fibre characteristics can be monitored in flowing suspension of fibres by measuring heat transfer coefficient and using those measurements to adjust the degree of fibre refining treatment so that papers made from those fibres are more uniform, more consistent and within product specification.

1. Introduction

Even at low populations the flowing flexible elastic fibres in suspension form collide and entangle. Fibre bundles or flocs can behave differently from the individual fibres of themselves. Three-dimensional floc structures or networks develop with the increase of fibre concentration in suspension which occupies the entire pipe volume. Thus the transport properties and the shear mechanisms of the suspension are markedly different from other slurries and suspensions [1].

The frictional pressure loss of suspensions is significantly greater than that for water alone at low flow velocities but at elevated velocities and shear rates the dispersed fibres and fibre fragments of suspensions contribute to the reduction of the friction loss below the level for water (drag reduction) by damping turbulence. Between plug flow and fully-developed turbulence in the transition region fibres, fragments of flocs, and a network core coexist, which provide the very different momentum transfer mechanisms. Fibre structures of interlocked nature and elastic fibres can act as a solid continuum to enhance momentum transfer. Flexible fibres and flocs having visco-elastic behaviour can damp

* Corresponding author. Tel.: +60 3 7967 4582; fax: +60 3 7967 5317.
E-mail addresses: salimnewaz@um.edu.my, salimnewaz@yahoo.com (S.N. Kazi), gg.duffy@auckland.ac.nz (G.G. Duffy), xdchen@suda.edu.cn (X.D. Chen).
[1] Tel.: +64 9 3737599x87805.
[2] Tel.: +86 512 6588 2767.

http://dx.doi.org/10.1016/j.applthermaleng.2014.11.072
1359-4311/

Nomenclature

a	radius of the circular duct, m
d	diameter of pipe, m
f	friction factor, (Fanning)
q	heat flux, W/m^2
u	velocity, m/s
ΔP	pressure drop, kPa
ΔT	temperature difference, K or °C
ε	height of roughness, m
ε/a	roughness height
λ	thermal conductivity, W/mK
μ	dynamic viscosity, kg/ms
ρ	density, kg/m^3
ν	kinematic viscosity, m^2/s
u_t	turbulent friction or shear velocity, $u_t = u_m\sqrt{\frac{f}{2}}$
Re_ε	roughness Reynolds number, $\mathrm{Re}_\varepsilon = \varepsilon u_t/\nu$

Nusselt Number $\mathrm{Nu} = h_c \cdot d/\lambda$
Prandtl Number $\mathrm{Pr} = c_p \cdot \mu/\lambda$
Reynolds Number $\mathrm{Re} = \rho \cdot u \cdot d/\mu$

turbulence, which develops a 'momentum transfer competition'. These competitive processes result in an initial increase in drag reduction, a maximum lowering in frictional pressure loss, which is followed by a decrease in drag reduction [2] with the increase of flow velocity.

The fibre-flocs-liquid interactions [3] govern the momentum and also the heat transfer. Thus it might be expected that the measurements of pressure drop and heat transfer coefficient should be closely related. Fibres obtained from different sources (different parts of the same tree), different processes (chemical treatments, mechanical refining at different levels, thermo-mechanical treatment, bleaching etc.) and due to their inherent variable fibre characteristics (length, flexibility etc.) have an impact on suspension heat transfer and friction loss.

The proper design of fibre processing plant and the end product manufacturing plants could be correlated strongly with the knowledge of the friction loss and heat transfer characteristics of the suspensions of the processed fibres. The work reported here further throws some light onto the heat and momentum transfer mechanisms in the flowing fibre suspensions and provides a correlation between them and the fibre and paper properties. The results could finally open up a basis for further investigations relating to reduction of production loss in fibre final product processing plants.

2. Literature review

Properties of fibres in suspension form are a matter of concern in a diverse range of industries such as pulp processing, paper making, paper processing, fibre composite manufacture, textile manufacture, long-chain polymer processing, packaging etc. Closed conduit flow of fibre suspensions has been studied with the emphasis on the effect of fibre dimensions on turbulent drag reduction [4,5]. So far little work has been reported on heat transfer to fibre suspensions. Middis et al. [6] studied heat transfer and friction loss of fibre suspensions prepared from wood pulp fibres and nylon filaments to study the influence of fibre stiffness and aspect ratio (length to diameter ratio) on heat transfer and frictional pressure drop. They had given their main attention to fibre concentrations of more than 2% where fibres entangle and form network structures. Later Kazi et al. [7] worked with fibre suspensions of low consistency and studied heat transfer and frictional pressure drop of wood pulp fibre suspensions of different quality flowing in a pipe. They reported that the reduction of heat transfer coefficient was due to the effect of fibre on turbulent phenomena at low concentrations (<0.4%). On the other hand Middis et al. [6] had noted that at higher concentrations the reduction of h_c is caused by the development of a thin shear layer between the pipe wall and the fibre plug network (interlocking fibres). Later Duffy et al. [8] considered these findings and correlated h_c with fibre and paper properties. They observed that at low fibre concentrations little alterations in fibre properties are sensed by little change in h_c. The h_c values are altered with the variation of flow velocity, concentration of fibre (population), length, flexibility, coarseness (mass per unit length), surface topography and the amount of fibrillar fines present in the suspension. They reported that, the trends in the data of h_c could be correlated and utilised to predict specific fibre and paper properties. This should go a long way in diminishing paper quality changes and the retardation of the production of low quality or reject papers. Frictional pressure drop $\Delta P/L$ data [9] were incorporated in the study and satisfactory correlations were also achieved with fibre and paper properties.

Recently some investigators have been focused on spatial and oriental distribution of fibres in various flow fields with numerical and some experimental approaches [10–15]. Olson and Kerekes [16] have reported numerical simulation and experimental validation of spatial and orientation distribution of fibres in various flow fields. Some investigators have further extended the investigation by incorporating research on shear flow behaviour of fibre suspensions [17–19]. Extensions of previous works were undertaken to study further and correlate fibre properties related to sources, extent of processing etc., to heat transfer and friction loss suspension characteristics. A new pipe flow loop was built to study the suspension flow behaviour and corroborate the results from previous pipeline studies [8]. The present work has aimed to generate more data experimentally for future development of valid models of turbulent fibre suspensions and introduce insight on the advancement of fibre processing and reduction of paper production loss by on-line monitoring of h_c or friction loss of suspensions.

3. Experimental

3.1. Pipe line flow loop

A schematic diagram of the experimental test loop is presented in Fig. 1a. The flow loop consists of a tank, a variable-speed driven pump, a magnetic flow meter, pressure transducers, heated pipe test section, coolers and a recycle piping system. The fibre suspensions are pumped by an Allis-Chalmers PWO Stock pump from the 400 L capacity steel tank. The pump is driven by a 20 kW AC motor which is controlled by a Plessy variable speed AC controller.

As per requirement the suspension flow could either be recycled directly to the tank or directed through the flow loop. The downstream pipe diameter is made the same as the test section. The fibre suspension flow was measured by a 50 mm bore ABB Kent–Taylor Electromagnetic flow meter (calibrated in the range 0–20 L/s) installed before the test section. Heat gained by the test liquid at the test section is cooled by a coaxial pipe heat exchanger and a submerged coil-cooler in the tank. The flow loop piping except the test section is Class D, 50 mm, pressure 800, PVC pipe. Details of the test set-up are presented elsewhere [20,21].

3.2. Heat transfer test section

The heat transfer test section was designed and constructed at the University of Auckland. The sectional view of the experimental test section is presented in Fig. 1b. The heat transfer test section is