

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



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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.

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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.

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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

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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
e	height of roughness, m
e/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, $u_t = u_m \sqrt{f/2}$
Re_e	roughness Reynolds number, $Re_e = \epsilon u_t / \nu$
Nusselt Number	$Nu = h_c \cdot d / \lambda$
Prandtl Number	$Pr = c_p \cdot \mu / \lambda$
Reynolds Number	$Re = \rho \cdot u \cdot d / \mu$

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

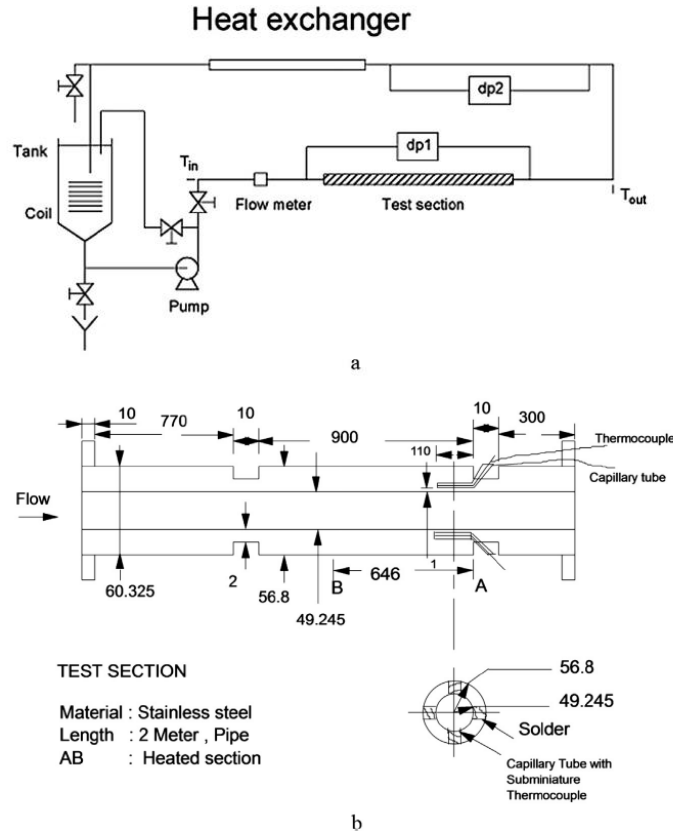
3.1. Pipe line flow loop

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 Plessey 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



0.646 m long and of 49.245 mm internal diameter stainless steel 316 L pipe. Ten band heaters are installed by clamping outside and along the test section to provide the source of thermal energy to the flowing liquid.

Test section inside wall temperatures were obtained from four thermocouples of type-E. The thermocouples are embedded in the pipe wall radially near the inside surface approximately 110 mm from the exit end of the heated section. The friction loss measurements across the test section and over a length of the PVC return line from test section exit and the heat exchanger were measured by two Kent differential pressure transducers. The main dimensions of the experimental test section are presented in Table 1 and details of the test section are presented elsewhere [20,21].

Table 1
Dimensions of the test section.

Parameters	Values
Overall length	2 m
Inside diameter	49.25 mm
Heated length	646 mm
Thermal entry length	536 mm
Hydrodynamic entry length	4785 mm

3.3. Experimental procedure

Bleached Kraft softwood pine pulp of different grades from Forest Products Ltd. of New Zealand, were used in these experimental investigations. The pulp sheets were soaked for a minimum of 18 h and then dispersed. The dispersed pulp fibres were taken into the tank and recycled by pumping the suspension through the by-pass line. The fibres were recycled for 30 min to disperse them completely. In the experiments the bulk velocities were maintained at 0.3–4 m/s while temperatures were simultaneously measured with the thermocouples located both in the wall and at the centre of the flow.

Table 2
Experimental parameters.

Variable parameters	Range
Velocity range for heat transfer	0.26–1.3 m/s, ΔT 15 °C
Velocity range for pressure drop	0.26–10.5 m/s
Suspension bulk temperature	30–40 °C
Wall surface temperature	19–50 °C
Surface to bulk temp. difference	15 ± 0.05 °C and 5 ± 0.04 °C
Fibre concentration	0.05–0.4%
Heat flux	4.0–85 kW/m ²

At the beginning and end of each run, the fibre samples were taken to obtain the fibre concentrations. Suspension samples were weighed, filtered, dried in an oven and reweighed to obtain the concentrations of the fibres as the percentage dry fibre mass per mass of total suspension. A summary of experimental conditions is presented in Table 2.

3.3.1. Fibres

Chemically processed (Kraft) bleached wood pulp fibres of pine soft wood having different coarseness values (fibre mass/unit length) such as Hi, Med, Lo and ULo coarseness, a market Kraft spruce pulp, a bleached short-fibre eucalypt pulp and a market Kraft bleached pine pulp were used in this investigation. Fibre specifications are presented in Table 3 and elsewhere [22].

3.4. Data processing

A Hewlett Packard data acquisition system and a computer were used for recording data of inlet and outlet temperatures, wall temperatures, heater power input, flow rate and pressure drop. Heat flux q is the energy input to the heater per unit surface area which is representing the total power input divided by the heated area A . The temperatures T_w at the heater wall were evaluated from the thermocouple readings T_{tc} taken in the test section using calibration correction factors for the distance of the thermocouples below the pipe heater surface. The temperature differences between the thermocouples embedded in the wall and the real surface temperatures are therefore obtained by multiplying heat flux with the wall resistances x/λ , as presented by Equation (1).

$$T_w = T_{tc} - q/(\lambda/x) \quad (1)$$

The local heat transfer coefficient h_c is obtained from the evaluated average wall temperature T_w , the bulk temperature T_b and the heat flux q , as shown by Equation (2).

$$h_c = q/(T_w - T_b) \quad (2)$$

The bulk temperature T_b is the position-weighted average calculated value from the inlet and outlet temperatures (T_i and T_o respectively). Equation (3) presents bulk temperature as a function of inlet and outlet temperatures. This was based on the assumption that the fluid temperature is increased linearly over the heated section and remained constant in the unheated sections of the rig. This is reasonable because the temperature rise between inlet and outlet thermocouples was normally less than 1 °C.

$$T_b = T_i + \frac{536}{646}(T_o - T_i) \quad (3)$$

The values of friction factor f are calculated by Equation (4) from the data of pressure drop per unit length $\Delta P/L$, bulk velocity u , pipe diameter D and suspension density ρ .

$$f = (\Delta P/L)(D/2\rho u^2) \quad (4)$$

In the previous investigations and also in the present studies the thermo-physical properties of water at the specified parameters were chosen as the properties of fibre suspension. Wherever predicted values were compared with experimental data or data reproduction were concerned an estimation of the goodness-of-fit was evaluated from the root-mean square (rms) error. This is presented by Equation (5).

$$\text{rms error} = \left[\frac{1}{n} \sum_{i=1}^n (X_{\text{pred}} - X_{\text{meas}})^2 \right]^{1/2} \quad (5)$$

where, $(X_{\text{pred}} - X_{\text{meas}})$ is the difference between predicted and measured data point. The rms error was selected as it is not subject to algebraic cancellation of positive and negative differences and the result is not unduly affected by a single erroneous data point.

4. Results and discussion

4.1. Calibration of test loop with water

Friction loss and heat transfer data for water-alone and the obtained correlations were compared with published correlation equations.

The calibration experiments were conducted at a constant bulk temperature and temperature difference of 30 °C and ΔT 15 °C (wall-liquid) respectively. Friction factor f (Fanning) and heat transfer coefficient h_c versus Reynolds number Re at ΔT 15 °C are presented in Figs. 2 and 3 respectively.

Friction factor data obtained from measurements over the test section and a portion of return pipe agreed well with the Colebrook and White correlation Equation (6) which includes the effect of roughness [23]:

$$1/\sqrt{f} = 3.48 - 1.7372 \left[\ln \left(\epsilon/a + 9.35/Re \sqrt{f} \right) \right] \quad (6)$$

where, a represents the circular duct radius and ϵ is the roughness height. Good agreement (data remains within 95% confidence level with average rms error 5%) between the experimental and theoretical results were obtained with a roughness height ϵ/a , of 0.0012.

Heat transfer coefficient data were compared with the calculated values from the Martinelli correlation (Equation (7)) for turbulent fully developed and fully rough flow regime of a circular duct [24]:

$$Nu = \frac{RePr\sqrt{f/2}}{5 \left[Pr + \ln(1 + 5Pr) + 0.5 \ln \left(Re\sqrt{f/2}/60 \right) \right]} \quad (7)$$

Table 3
Properties of Kraft fibres used in the experimental investigation [20].

Fibre type	Width, W μm	Thickness T μm	Cell wall thickness t mm	Diameter D μm	Length L mm	L/D	L/P	Wall area μm^2	RFN	Meas. stiff. 10^{-11} Nm^2	Coarseness mg/m
Hi	30.4	10.5	3.57	30.4	2.60	85.5	31.8	202	76	0.331	0.250
Med	30.1	9.2	3.11	30.1	2.24	74.4	28.5	177	100	0.251	0.209
Lo	30.5	9.2	3.05	30.5	2.08	68.2	26.2	174	110	0.205	0.200
ULo	30.4	9.0	2.96	30.4	1.88	61.8	23.9	169	125	0.164	0.184
Sp	25.1	8.9	2.57	25.1	2.49	99.2	36.6	130	123	0.167	0.198
Eu	12.7	6.9	2.48	12.7	0.74	58.3	21.2	—	927	—	0.187
BK	—	—	—	—	2.53	—	—	—	80	—	0.246

RFN: Relative number of fibres per unit mass with Kraft pine Med being the basis.
BK: Bleached market Kraft fibres (Standard).

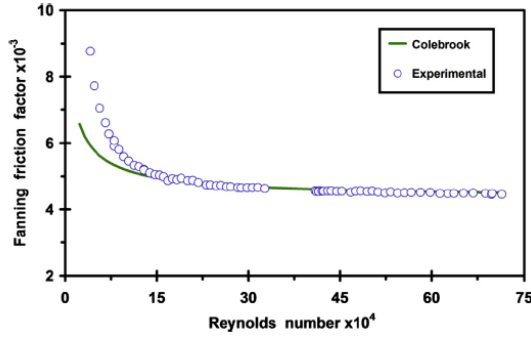


Fig. 2. Fanning friction factor f versus Reynolds number Re for water showing experimental and empirical values. Bulk temperature 30°C and ΔT 15°C .

Data obtained experimentally also satisfied the predicted values from the Martinelli equation within 95% confidence level with a rms error 5% at specified Reynolds numbers.

4.2. Data reproducibility

In this study data reproducibility was conducted by two water runs and heat transfer coefficient compared as a function of velocity at a temperature differential (ΔT) of 15°C and bulk temperature of 30°C . The data reproduced well and remain within the confidence level of 95% and rms error $<2\%$. The details and relevant graphical data are presented elsewhere [20,21].

Similarly the frictional pressure drop ($\Delta P/L$) data from two water runs at ΔT 15°C and 30°C bulk temperature shows good agreement and remains within 95% in the confidence level with average rms error $<4\%$. Graphical data and details are presented elsewhere [20,21]. However the present investigations have been conducted in a highly reproducible test rig for both the heat transfer and frictional pressure drop data.

4.3. Heat transfer to fibre suspensions

4.3.1. Effect of fibre concentration

Study of the concentration affect on heat transfer to fibre suspensions were conducted by a series of experiments with

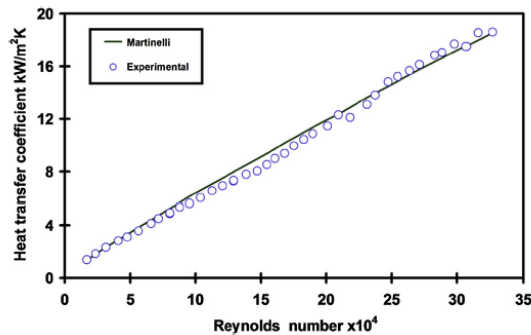


Fig. 3. Heat transfer coefficient h_c as a function of Reynolds number Re for water showing experimental and empirical correlations. Bulk temperature 30°C and ΔT 15°C .

bleached Kraft pulp suspensions of different mass concentrations. Fig. 4 represents heat transfer coefficient as a function of velocity for bleached Kraft fibre suspensions at different fibre mass concentrations (0.05, 0.1, 0.15 and 0.25%) at ΔT 15°C and bulk temperature 40°C (velocity range varied from 0.26 to 1.5 m/s). At a very low velocity of around 0.26 m/s, little distinction is observed in the heat transfer coefficient values. With the increase of velocity up to about 0.8 m/s, the heat transfer coefficient of the highest concentration of fibre suspension 0.25% shows a distinct demarcation and produces the lowest heat transfer coefficient values. Suspensions of all the concentrations except the highest 0.25% have h_c values close to the water data up to 0.8 m/s. At higher velocities the data points are separated on the basis of concentration and they move towards water values again at further higher flow rates. In general at each velocity point the highest value of h_c occurs when the fibre concentration is the lowest. It is noted that fibres in suspension at very low concentrations enhance heat transfer coefficient to a significant value and the h_c values gradually approach the water value as the concentration of fibre increases. At higher concentrations the h_c values of suspensions are below the water data. Similar results were obtained by previous researchers [25,26].

4.3.2. Fibre processing affect on heat transfer characteristics

4.3.2.1. Effect of bleaching. Fibres from a natural wood source are processed differently in the paper pulp industry to meet different particular requirements of the intermediate and final products. Removal of lignin loosens the cell wall structure allowing water molecules to get between the microfibrils and thus lower Young's modulus. Loosening of the cell wall structure is followed by an inward motion of the fibrils into newly vacated spaces during pulping as well as beating. The cross-dimensional fibre properties deteriorate during pulping. Cell wall thickness reduces by 50% and the width of fibre 15% respectively when pulp is cooked to 40% yield [27]. Pulping increases the tendency of fibres to collapse and in this way also lowers the moment of inertia. Fibres are made more flexible in the bleaching process. The flexibility of unbleached pulp fibres is 68% of that of bleached pulp fibres measured using the Steadman method and 83% of that measured using the TamDoo and Kerekes method [27]. Mohlin reported the severe influence of bleaching on wet fibre flexibility [28].

In Fig. 5 heat transfer coefficient is presented as a function of velocity for water and unbleached and bleached Kraft pulp fibre suspensions at 0.15% concentration, temperature differential ΔT 15°C and bulk temperature of 40°C . It is observed that at a very low velocity <0.4 m/s, h_c values for unbleached and bleached are similar. At velocities >0.4 m/s, there is a small difference between

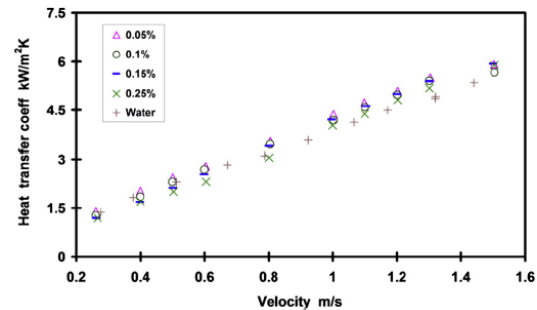


Fig. 4. Heat transfer coefficient as a function of velocity for water and four different concentrations of bleached Kraft pulp fibre suspensions. The experiments were performed at ΔT 15°C and bulk temperature 40°C .

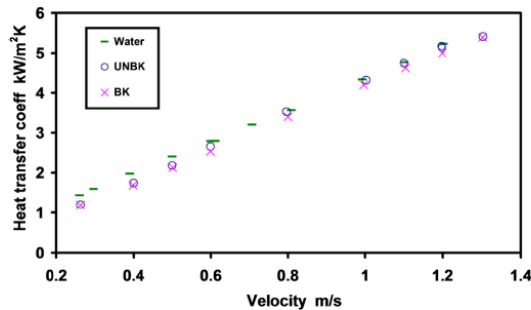


Fig. 5. Heat transfer coefficient as a function of velocity for water, unbleached and bleached Kraft pulp fibre suspensions. The experiments were performed at fibre concentration 0.4%, ΔT 15 °C and bulk temperature 40 °C.

unbleached and bleached fibre suspensions. At 0.8 m/s velocity the bleached pulp fibre suspension is about 3.5% below the unbleached fibre suspension due to higher flexibility. Heat transfer characteristic of the processed fibres is a unique measurement to estimate the effect of a particular processing event on the fibre.

4.3.2.2. Effect of freeness. One of the most important treatments given to the fibres prior to paper formation is that of beating. Beating has a brushing, rubbing and crushing effect on fibres. Fibres are made increasingly flexible as beating periods are extended [29].

Thus due to refining some of the amorphous material is removed and fibre swelling occurs. As a matter of fact the conformability increases. Various methods of measuring the drain ability of pulp correlate with its papermaking properties. The advantages of measuring pulp suspension properties before paper sheet formation are the opportunity to modify the fibres before they are presented to the papermachine to minimise poor quality and out-of-specification paper. Drainage measurements (freeness) can be automated and made on-line which opens up new potential for process control [30,31]. Thus heat transfer characteristics correlated with the drainage properties of suspensions could be a means to govern process control by a secondary means.

Fig. 6 represents heat transfer coefficient as a function of velocity for softwood fibres of two different freeness levels (200 and 500 CSF) in suspension form. The suspension bulk temperature was maintained at 30 °C, temperature differential between surface and

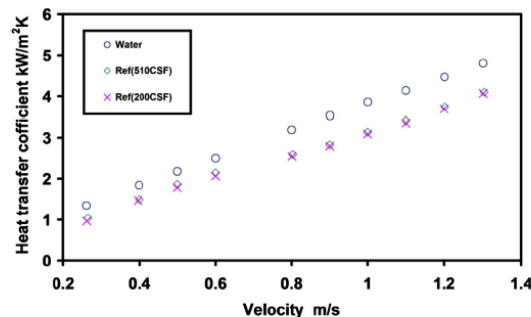


Fig. 6. Heat transfer coefficient as a function of velocity for water and refined (two different degree of refining 200 and 510CSF) fibre suspensions. The experiments were performed at ΔT 15 °C, bulk temperature 30 °C and fibre concentration of 0.4%.

bulk as 15 °C and the suspension concentration as 0.4%. It is observed that the heat transfer coefficient decreases slightly with the increase of fibre suspension freeness. At 0.4 m/s velocity heat transfer coefficient of a suspension of fibres where the fibres have been refined to a freeness of 200 CSF is above 80% of the water value. At 510 CSF it is 81% of water. The refining freeness of the suspension relationship is sensed by a small change in heat transfer coefficient.

Fig. 7 represents heat transfer coefficient as a function of velocity for water and two grades (200 and 500 CSF) of TMP (Thermo mechanical pulp) fibre suspensions concentration (0.4%, ΔT 15 °C and bulk temperature 30 °C). As observed in the previous case of Fig. 6, heat transfer coefficient decreases with the increase of fibre refining and decreasing freeness. At a velocity of 0.4 m/s and for TMP (200 CSF) the lowering is to a value of 62.5% of water. For TMP (500 CSF) the lowering is to a value of 69% of water. TMP pulp fibres are more flexible than chemical pulps [32,33] so the lowering of h_c is more noticeable in TMP in comparison to chemical pulps (Figs. 6 and 7).

4.3.2.3. Effect of refining on h_c to fibre suspensions (MDF pulp fibre). The MDF (Medium Density Fibreboard) fibres with more retained lignin are stiffer and there is more refining energy needed to make the MDF fibres more flexible. In Fig. 8 heat transfer coefficient is represented as a function of velocity for water, fibre suspensions of three different grades of MDF refined fibre at three different energy levels (MDF High, MDF Medium and MDF Low).

During the experiments ΔT was maintained at 15 °C and fibre concentration and bulk temperatures were maintained at 0.4% and 30 °C respectively. It is observed that for the three MDF fibres there is a progressive lowering of the coefficient h_c as more refining energy is used to make the MDF fibres more flexible. It is observed that at 0.4 m/s velocity the lowering of heat transfer coefficient for MDF (Low), MDF (Medium) and MDF (High) are 3.3, 19.9 and 25.1% of water respectively. With the increase of velocity the h_c values of the suspensions are increased keeping the same trend.

4.3.3. Effects of fibre flexibility, length and population on heat transfer to fibre suspensions

The ability of wet fibres to deform is characterised by flexibility. Previous researchers have [20,27] reported that wet-fibre flexibility is dependent on cross dimensional fibre properties and increases with the decreasing cell wall thickness. Fibre network structure and bonding are dependent on flexibility characteristics which affects paper properties as well. By modifying the wet-fibre flexibility

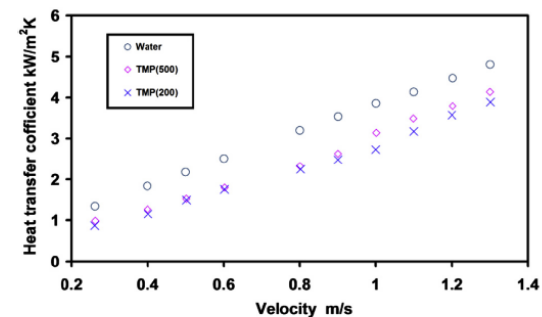


Fig. 7. Heat transfer coefficient as a function of velocity for water and fibre suspensions of two grades of TMP (Thermo mechanical pulp). The experiments were performed at ΔT 15 °C, bulk temperature 30 °C and fibre concentration of 0.4%.

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