Flow phenomena and paper forming.

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SUMMARY

The channel flow phenomena of the University of Melbourne stationary wire laboratory former were investigated to further the understanding of the effect of flow conditions on sheet properties. The flow phenomena above the wire in the z-MD plane immediately prior to and during de-watering were investigated using images collected with a 16mm high speed ciné camera (200 frames per second). The flow regimes were observed to be consistent with pipe flow studies in that a plug flow with a turbulent boundary layer was evident. The mechanism of forming was found to be via a boundary layer filtration process. The hydraulic behaviour of the system was characterised the Froude number.

INTRODUCTION

During the last century there was a significant effort to understand the flow phenomena of pulp suspensions in pipe flow (*1*,*2*, *3*), channel flow (*4*), headboxes (*5*) and on the wire on a commercial paper machine (*6*, *7*). The flow regimes of pipe flows which were identified included, plug flow, mixed flow, and turbulent flow, which were dependent upon the flow geometry, suspension type and consistency, and driving force. In many of these flow investigations the use of direct observation and image analysis of the flow was crucial to identifying the various flow regimes. To date there has been no direct investigation of the z-MD plane flow structure on the wire during paper forming. This can be attributed to difficulties posed by the high operational speeds, the nature of pulp suspensions, the risk of damage to the machine, and the inconvenience to papermakers.

Current understanding of the flow structure on the wire is largely restricted (*8*) to the mechanisms identified by Parker (*9*) which include drainage forces, oriented shear, and turbulence, as shown in figure 1.

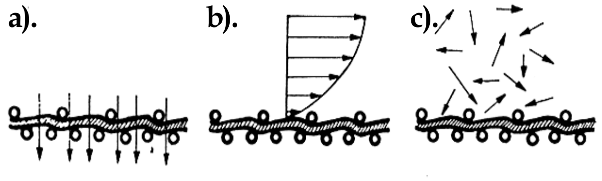

Figure 1: Flow on the Wire, a). Drainage, b). Oriented Shear, and, c). Turbulence.

Parker (*9*) also proposed two drainage mechanisms; filtration and thickening. Filtration is widely considered to be the mechanism by which commercial paper is made (*10*). Whilst these concepts have made a significant contribution to the understanding of the effect of process conditions on paper properties, the understanding is still largely qualitative and the sequence of events which culminate in fibre deposition is still unclear. Furthermore, this lack of knowledge has hindered the development of laboratory formers which accurately simulate the commercial papermaking process.

The devices which have been available to form sheets in the laboratory are quite varied in their design and operation (*11*-26). The fine structure of sheets produced on many of these laboratory formers differs quite markedly from paper which has been made on a commercial paper machine (*20-22*). Further problems with grammage profiles and fibre fractionation have also been reported (1*6-18*). The devices which have produced paper similar to a commercial machine have been reported to be bulky, difficult to operate and hard to control (19). None of these devices has been deemed to be a truly satisfactory predictor of what may be expected on a commercial machine from a given fibre stock. Furthermore, they are generally unsuited to investigating the mechanism of fibre deposition and the effect of process conditions on the structure of paper formed commercially. Thus, there is no device which predicts the papermaking potential of particular fibre sources with a degree of precision which approximates the achievements of pilot paper machines, and without the expense and logistical complexity of a pilot scale trial.

The flow above the wire in the forming region of a commercial Fourdrinier former has been classified as being equivalent to a high aspect ratio, rough channel flow and a new laboratory former, the University of Melbourne (UoM) former has been developed (*27*) as a tool for studying the behaviour of pulp stocks in a system equivalent to a commercial papermachine. In this study, the flow phenomena above the wire on the UoM former has been investigated to gain insights into the commercial forming process.

THEORY

The modelling perspective used throughout this study has involved a temporal mechanics analogy and dimensional analysis of a high aspect ratio rough channel flow. The development of the model (UoM laboratory former) was reported in an earlier paper (*27*).

UoM Forming Concept.

The fibre orienting effect of the jet to wire ratio (rush/drag) is well documented (*28,29*). The effect of jet to wire ratio on fibre orientation has been re-interpreted to be more accurately expressed as arising from the velocity difference between the jet emerging from the headbox and the velocity of the wire (*30*). This observation formed the basis for the conceptual design of the current apparatus. The conceptual approach is similar to the "moving with the flow" type analogy often used in fluid dynamics where a frame of reference having a mean velocity is used to convert a spatial domain into a temporal one (*31*). The speed of the wire, V_w (m/s) corresponds to the observer velocity in this case. Thus, the operational velocity (overall machine speed) was much reduced. The analogy used for the design of the laboratory model is depicted below in figure 2.

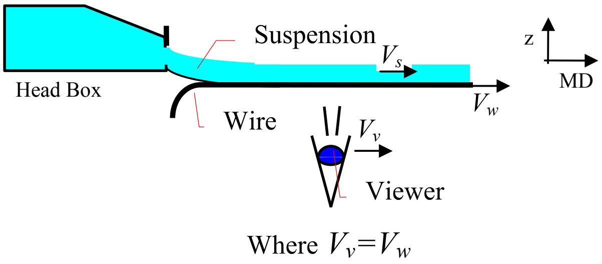

Figure 2: The UoM model analogy, (where V = velocity (m/s) and subscripts, s = suspension, w = wire, and v = viewer).

Many Fourdrinier machines have a de-watering profile where significant de-watering occurs some distance down the forming table and hence are characterised by a region of channel flow development. The stationary wire model used in this study *directly* simulates the flow structure of commercial Fourdrinier formers which have a fully developed channel flow prior to de-watering, and *indirectly* those which do not[1]. The point of similarity between the stationary wire model and the commercial forming process is depicted in figure 3.

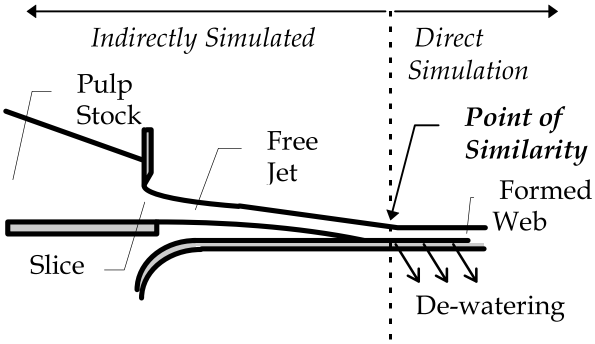

Figure 3: Similarity of the model and the means of simulation for commercial machines with fully developed channel flow.

The conceptualisation allows a simple relation between the commercial process operating parameters and the laboratory control parameters. These relationships are presented elsewhere (*32*).

Channel Flow and Dimensional Analysis.

A system is characterised by its geometry and the forces acting, its dynamic similitude (*33*). Prior to de-watering, the flow in the model was considered to be equivalent to a high aspect ratio, rough, rectangular channel flow issuing from under a weir gate. Open channel flow is similar to closed conduit flow and pipe flow but the flow mechanics are more complex due to the presence of a free surface. Gravitational force causes the flow of the free surface whilst the viscous shear forces along the wetted perimeter retard the flow. The geometry of very wide channels (those with a high aspect ratio) is characterised by the depth, d(m). (*34*)

Both the Reynolds number and the Froude number are important for characterising the flow in channels[2] with respect to the balance of the forces acting. The Froude number has the greatest significance for the flow in channels and is a useful means of classification. The Reynolds number is useful for determining the flow regime and the onset of turbulence for Newtonian fluids,

The Reynolds number for channel flow is defined as;

$$\mathrm{Re} = \frac{\overline{v}d}{\nu} \qquad \text{Eq. 1}$$

where,

$\overline{v}$, velocity, (m/s), and,
ν, kinematic viscosity (m^2/s).

The Froude number[3] for channel flow is defined as;

$$Fr = \frac{\overline{v}^2}{gd} \qquad \text{Eq. 2}$$

where,

g, gravitational acceleration, (m/s^2).

Channel flow (*34*) may be classified as *steady* or *unsteady*, *uniform* or *non-uniform*, and *rapid* (alternatively, "supercritical") or *tranquil* ("subcritical") based on the observed flow behaviour and flow properties. A steady

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[1] Note that the effect of table elements such as foils acting on the flow are not *directly* simulated in its current state of development. However, these may be *indirectly* simulated by achieving flow structures in the laboratory forming region consistent with the flow structure *after* the influential table elements by manipulating other laboratory process variables, (e.g. the consistency), if the these process operations de-water the stock without the development of a mat. It may be considered that the point of similarity is thus moved further downstream of the slice in figure 3.

[2] and also mixing systems.

[3] Sometimes the Froude number is also defined as: $Fr = \overline{v}/\sqrt{gd}$, (*34*).

flow has a constant discharge rate, an unsteady flow does not. A uniform flow has a uniform depth and velocity profile throughout the channel, a non-uniform flow does not. A rapid flow has a high velocity which sweeps flow disturbances down stream and is classified by a Froude number greater than 1. Tranquil flow is characterised by a Froude number less than 1 and has a low velocity where flow disturbances will extend back upstream. A rapid flow may suddenly change to a tranquil flow with a sudden increase in the elevation of the liquid surface. This phenomenon, known as a *hydraulic jump*, converts the kinetic energy of a rapidly flowing stream to potential energy and losses or irreversibilities. This phenomenon is shown in figure 4.

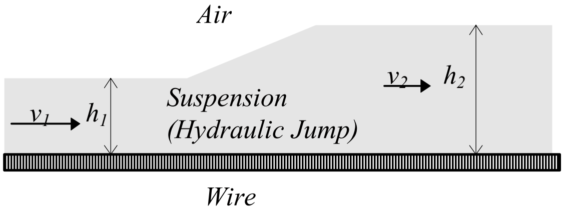

Figure 4. Hydraulic Jump in Channel Flow, ($h_2 > h_1$).

The laboratory model design challenge was to create an area in the MD-CD plane of uniform depth and flow properties, a stable channel flow.

APPARATUS

The UoM employed a 1:1 scale due to the complex rheology of pulp suspensions and was designed according to the principles and considerations of a high aspect ratio, rough, rectangular channel to achieve a steady uniform flow. The features of the UoM former channel system are shown in figure 5.

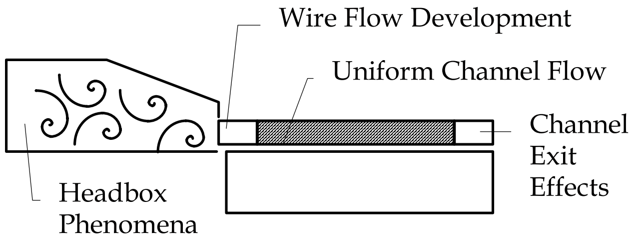

Figure 5: The conceptual operation of the establishment of uniform channel flow in the model.

The development of this former was discussed in an earlier paper (*27*).

The principle components of the UoM sheet former include:

1. a novel multi slice headbox (CD_y width 400mm),
2. a large single pulse vacuum box (MD_x forming length 500mm, CD_y width 400mm),
3. a 110L head tank,
4. a 110L receiver tank
5. a customised reducing diameter bifurcated distributor,
6. a large vacuum reservoir, and,
7. a centripetal pump.
8. a plate to support the flow prior to forming arranged in a manner so that the support is withdrawn rapidly,
9. a self supporting flow receiver with fixed transparent walls which extend right up to the headbox,
10. a fast closing gate valve to halt the flow, and,
11. an automated integrated control system.

The components were assembled as shown in figure 6 below, to establish a re-circulating flow loop.

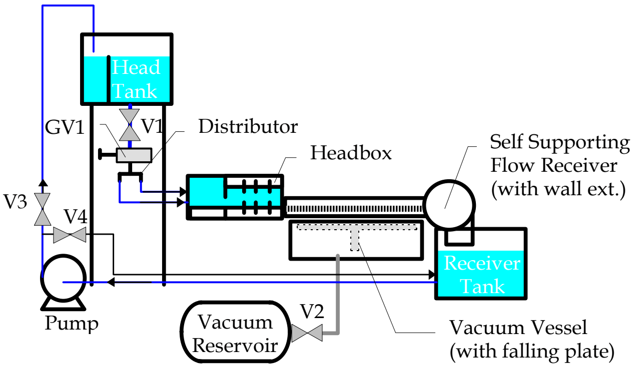

Figure 6: Schematic diagram of the basic components and the configuration of the laboratory former.

Prior to de-watering the system is controlled manually. The de-watering is controlled by an integrated control system involving electronic timing of a pneumatically actuated mechanical control system, which was discussed in an earlier paper (*27*).

PROCEDURE

Stock Preparation.

The stocks used in this investigation were prepared by suspending measured quantities of air dried, un-refined, dry lapped, bleached kraft tropical hardwood pulp (Brightness 90% ISO) or Bleached Eucalypt Kraft pulp (Brightness 88% ISO). A small amount of commercial Sodium hypochlorite was added to prevent bacterial growth, (10 ml into the 200L system).

UoM Operation.

The system was initially adjusted to the settings shown in Table 1, with BEK.

Table 1
Mk II Former Parameters.

Parameter	Value	Precision
Slice Height	10 mm	± 0.25 mm
System Head	1 m-stock	± 0.01 m
Vacuum Time	0.6 s	± 0.02 s
Reservoir Vacuum	50 kPa (gauge)	± 0.5 kPa

Mass of Stock	1 kg	± 0.010 kg
System Volume	200 L	± 5 L

The operation of the UoM former involves the establishment of a stable re-circulating flow loop, followed by subsequent sampling and recording of the process variables. The settings in Table 1 resulted in the following process conditions; consistency $c =$ 0.5 $^{w}/_{w}$ % (~5 g/l), Vacuum peak ΔP_{max} = 7.2 kPa, and a height over wire, h = 10 mm. The mean velocity was adjusted using valve V1 in figure 6. Changes to the consistency were effected by adding further stock or by diluting the system with water.

Forming was initiated by the operator activating the electronic control system. The wet sheets were couched on to sheets of blotting paper (~200 gsm, 42 x 57 cm^2) with a layer of thin woven nylon mesh interposed between the wet sheet and the blotting paper to facilitate separation of the sheet and the blotting paper after drying. Further de-watering was achieved by pressing manually against additional dry blotting paper with a hand roller. No other pressing was used. The sheets were allowed to dry freely in open atmospheric conditions.

Further operational details are reported elsewhere (*32*).

Process Variable Measurement.
Stock consistencies were measured gravimetrically by sampling directly from the flow receiver and filtering through pre-weighed, oven dry, analytical filter paper, (Whatman No. 541). The filter cake was then oven dried (110^{o}C) for 12 hrs before subsequent weighing. The mean stock velocity over the wire was determined by measuring the time taken for a neutrally buoyant particle to traverse the forming region (0.5m).

High Speed Ciné Analysis.
A Hycam II (16mm) operated at 200 frames per second with a telephoto lens was used to record images of the flow structure. The camera was positioned to record the flow in the z-MD plane through a transparent side wall, as shown in figure 7.

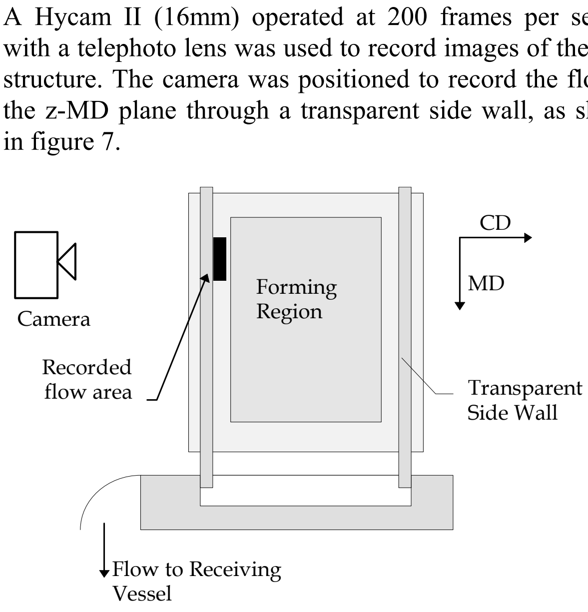

Figure 7: Location of Camera.

The lighting was adjusted to effect a reasonable contrast between the more and less dense regions of the flow.

The system was operated at various velocities and the flow behaviour was observed. The significant phenomena were recorded including a sheet was being formed at a mean velocity of 0.5 m/s. The ciné footage was converted to video format and the contrast was digitally enhanced. Prior to forming, the flow structures were also observed with the naked eye.

RESULTS.

A short video, (ca 3mins) of the image data collected during the study will be presented.

Flow Phenomena.
The footage which was captured is representative of that which was observed with the naked eye. A boundary layer at the wire was observed, (<1mm thick). At low to intermediate velocities the upper regions of the flow moved as a plug. The boundary layer interacted with the fibres in the suspension above. The extent to which the boundary layer interacted with the fibres above it was dependent upon the velocity. The boundary layer instabilities appeared to grow as the velocity was increased. During de-watering the flow continued until the flow depth had dropped to ca 1 mm. The fibres passed through the boundary layer before being deposited in the mat.

Tranquil flow was observed at velocities less than 0.32 m/s and downstream disturbances were observed to be communicated upstream, (i.e. the channel flow exit was the dominant control of the flow behaviour and disturbances were communicated upstream). At higher velocities the flow was rapid and the slice was the dominant control, disturbances were swept downstream. A hydraulic jump was observed to occur at a velocity of ca 0.32 m/s. The position of the jump could be controlled by fine adjustment the volumetric flowrate.

DISCUSSION

The flow structures observed were similar to those reported for pipe flows of similar stocks at similar consistencies (and velocities), where a boundary layer is developed at a surface and plug flow is observed (*1-3*). The significance of the boundary layer was manifest as the flow continued until de-watering was almost complete, i.e. the fibres passed through the boundary layer before being deposited in the mat and so there final position was influenced by the boundary layer shear.

Boundary Layer Filtration.
Observations of sheet forming on the UoM have led to a *boundary layer filtration* process being identified for fine paper stocks at consistencies used in conventional paper forming. In this process fibres pass through a region of high shear before becoming part of the fibre mat. The flow structure inherent to this process is depicted in figure 8.

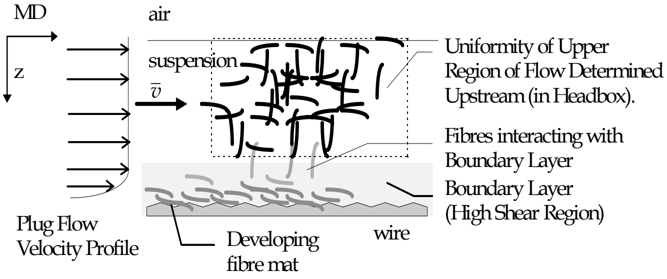

Figure 8. The importance of the boundary layer.

Implications for Laboratory Paper Forming.

A bias in the fibre orientation toward the MD is most commonly introduced by exposing a fibre to a shear force. This may be achieved by passing a suspension through a constriction, such as a slice, or by directing a flow over a rough surface to create a boundary layer, such as that which occurs on the wire of a papermachine. There are many reports (*29, 30*) that the velocity ratio of the jet to the wire, or more accurately, the magnitude of the *difference* between the jet velocity and the wire velocity is significant for controlling the structural characteristics of paper, (particularly the formation and fibre orientation, (*29, 35*)). The jet-to-wire difference is most often manipulated commercially by varying the wire speed. Hence, *fixed* flowbox operation. Thus the flow velocity relative to the wire accounts for much of the fibre orientation in paper, (although the fibre orientation induced in the jet is also significant). This interpretation argues that the mass formation of commercially formed sheets is affected by the wire operations whilst the uniformity of fibre dispersion achieved in the headbox contributes the basis from which the final formation is achieved. It is therefore reasonable to deduce that it is the *change in the flow structure* above the wire which is responsible for the dramatic *change in sheet properties*[4]. The visual analysis of the UoM channel flow during forming was in accord with this deduction. Furthermore, the results of this study, and a number of sheet forming investigations[5] (*32*) with the UoM former have identified the effects process variables have on the suspension flow above the wire and the subsequent effect of these flows on sheet characteristics. Hence, it may be argued that a laboratory former must achieve flow structures above the wire which are similar to those on a commercial papermachine *immediately prior to* and *during* de-watering if it is to achieve sheets with similar properties at similar operating conditions, (velocity, consistency, flow depth and vacuum), and accurately model the forming process.

Flow Phenomena Effects on UoM Operational Limits.

The operational range of the UoM laboratory former was affected by the flow phenomena of the pulp stock, the characteristics of a rough, high aspect ratio, channel flow and, control and handling constraints. The operational limits are summarised in figure 9, (the limits identified are valid for all pulps but the scales shown on the axes are valid for short fibre pulps only).

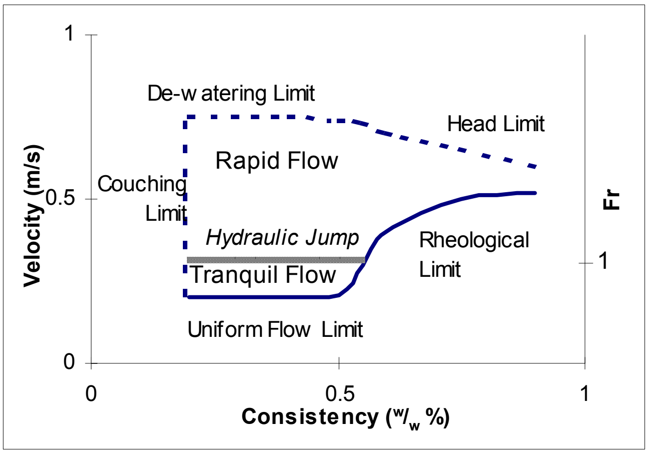

Figure 9: Mk II Stationary Wire Laboratory Former Operational Limits, (the axis is for short fibre pulps with a fixed system head only).[6]

De-Watering Limit.

The de-watering limit impacted on the size of the uniform region of a sheet that would be formed. At high velocities the end effects due to flow into and out of the forming region were magnified and reduced area of the sheet which was uniform, (e.g. the spillage from the headbox penetrated further along the wire affecting the mass uniformity of the sheet). The high de-watering rates used throughout the investigations acted to minimise the end effects arising from the flow.

Head Limit.

At high consistencies the upper limit of the velocity was constrained by the stock's increased resistance to flow, (increased consistency led to increased viscosity).

Rheological Limit.

At high consistencies the lower limit of the velocity was increased as the pulp exhibited a yield stress, (i.e. the flow would halt if the velocity dropped below this limit).

Uniform Flow Limit.

At very low velocities a significant incline of the forming wire in the MD was required to obtain a uniform flow. It was not possible to significantly incline the forming region as the operation of the flow support plate required a layer of water between the plate and underside of the forming wire and the water layer tended to drain at high inclinations.

Couching Limit.

The sheets which were formed on the Mk II Stationary Wire Former were relatively weak (unpressed and bulky)

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[4] Note: the increase in machine speed with modern development has not resulted in drastic increases in fibre orientation presumably because jet-wire speed differences have remained largely unchanged

[5] Some investigations are yet to be published.

[6] Constant depth (near critical), and constant vacuum operation.

and, when formed at basis weights less than 25 gsm, were easily torn during couching. The basis weight of sheets formed at low consistency was constrained by the flow depth which was limited by the critical depth of the channel flow and the establishment of uniform flow.

Flow Phenomena Effects on UoM Sheet Characteristics. A sheet may be partially characterised by its formation and fibre orientation. It is likely that these sheet characteristics are interrelated (*36*). The UoM laboratory former has been shown[7] to form sheets in a repeatable manner which are uniform and have properties akin to commercial paper in terms of both formation and fibre orientation formed at similar conditions (*32*).

The results from a process variable investigation performed in conjunction with this study (*32*) are considered in terms of the observed flow phenomena in figures 10 and 11. For constant depth and consistency (and hence the same basis weight), the effect of the velocity on formation may be summarised by considering the Fr of the system and the flow regime as shown in figure 10. A significant improvement in formation is observed as the system moves from tranquil flow to rapid flow. An optimum formation is observed after which the formation deteriorates as the plug flow diminishes and the de-watering rate is no longer sufficient.

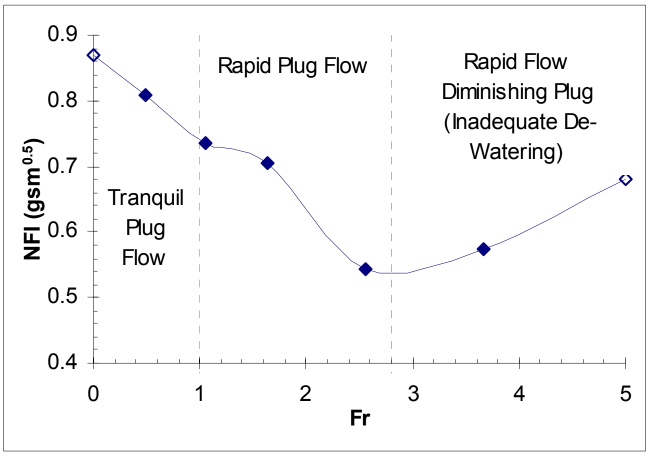

Figure 10: The effect of flow regimes on the wire prior to de-watering on formation, (hollow points are indicative of trend only), BEK 0.5 $^{w}/_{w}$ %.

Similarly, the fibre orientation expressed in terms of a fibre orientation index[8], (FOI) for the BEK stock at 0.5 $^{w}/_{w}$ % are shown in figure 11 as a function of the *Fr* of the system at constant depth.

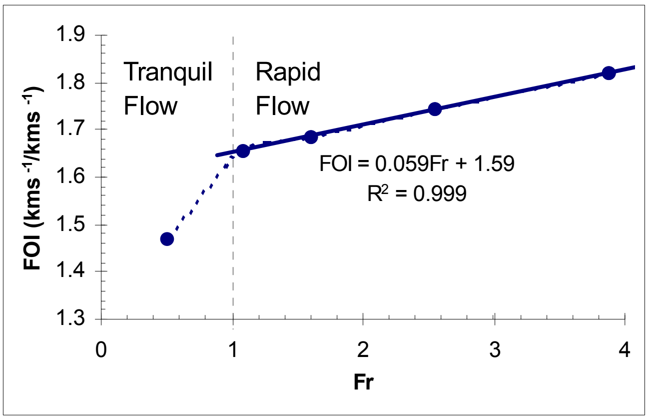

Figure 11: Mean FOI of the sheets formed at constant depth from 0.5 $^{w}/_{w}$ % BEK at various Fr.

It is clear from figure 11 that a change in the flow regime significantly affects the fibre orientation. Tranquil flows ($Fr < 1$) exhibit a different suspension structure which leads to lower MD fibre orientation. Rapid flows exhibit a gradual increase in the level of MD fibre orientation with an increasing *Fr*, and are well correlated by a linear relation for the range investigated, ($1 < Fr < 4$). The system was unstable at $Fr = 1$ ($\overline{v} = 0.32$ m/s and $h = 10$mm) with a change in the channel flow behaviour which affected the mechanism of fibre deposition and both the FOI and formation indices, (see (*32*) and note the spread in the data at the this condition).

Commercial Considerations.
The UoM operating diagram (see figure 9) may have implications for commercial operation. The rheological limit which develops at higher consistencies may be an important consideration for forming paper at higher consistency. If the jet to wire velocity difference is not great enough the flow will stagnate on the wire, possibly leading to poor formation. Figure 9 indicates that high jet to wire differences would be required to overcome the yield stress at these consistencies.

The quality of paper formed was observed to be greatly influenced by the flow conditions which were affected by the flow geometry and fluid properties. The *Fr* was found to characterise the hydraulic features of pulp channel flow and have a significant impact on both formation and fibre orientation. A rapid flow (viz. a reduced region of plug flow with a restricted turbulent boundary layer) results in the best formation whilst low flow rates led to tranquil plug flow and poorer formation. A transformation of flow behaviour from tranquil plug flow to a rapid plug flow ($Fr = 1$) was observed to occur at low velocity (ca 0.3m/s for a hardwood pulp).

The results of this study (and that performed in conjunction (*32*)) suggest that the flow conditions arising from the velocity difference between the suspension and wire, immediately prior to, and during de-watering significantly affect the distribution of fibrous material and hence the quality of paper which may be formed at particular operating conditions. The flow phenomena evinced in this

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[7] Note, the samples were circulated at the conference for expert scrutiny.

[8] Mean ultrasonic velocity ratio of four sheets formed at the same operating condition for each point, see (*32*).

study are thought to be representative of the flow behaviour which exists on the wire of a commercial papermachine.

The operation, control and on-line measurement of the process variables of the UoM laboratory former could be further improved to expand its operational range and usefulness. Further work to fully explore the relationship between the "moving with the flow" forming analogy as employed here, and the operation of a commercial Fourdrinier is in progress.

CONCLUSION

The hydraulic behaviour of the flow system was well characterised by the Froude number. The flow regime immediately prior to, and during de-watering significantly affected the disposition and deposition of fibrous material and hence the quality of paper. A boundary layer filtration mechanism was proposed to describe fibre deposition during forming.

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