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AN APPARATUS FOR DYNAMIC COMPRESSION STUDIES OF WET PAPER SHEETS

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Abstract

An apparatus for studying the dynamic compression of saturated paper sheets is described. The apparatus can generate various combinations of haversine and square wave press pulses. The dewatering during a full loading cycle is studied, that is in both the compression and expansion phases. The total applied load, the hydraulic pressure and the thickness of the sheet are simultaneously recorded during the pressing operation. A total pressure of 10 MPa can be applied in pulses of durations as low as 5 ms. The techniques for hydraulic pressure and thickness measurement are examined. The performance of the apparatus is demonstrated and results from press tests with sheets of different grammages and different degrees of beating are given.

Introduction

Water removal by pressing is of great economic significance in paper-making and the process has been the subject of many analytical and experimental studies. Several mechanisms are involved in the pressing operation, such as the compression behaviour and the permeability of the fibre mat.

Simplified models(1,2) have been extensively used in order to understand the water removal process in paper machine nips. Considering the complexity of the water removal process, it appears important to study consolidation of fibre mats under more simple experimental conditions in order to improve the basic understanding on the subject.

Studies of transverse dewatering between two parallel plates belong to the class of geometrical configurations which are simple enough to be suited to experimental analysis. The applied pressure can in this set-up be divided into two components; one borne by the fibre network, called the fibre structure pressure; and one borne by the water which we call the hydraulic pressure component: the sum of these two components being equal to the total applied pressure. The generated hydraulic pressure gradient creates a water flow out of the fibre mat and leads to increased dryness. The water flow is dependent on such variables as the degree of compaction of the mat and certain pulp characteristics.

Experimental investigations into how the applied pressure can be divided into a hydraulic pressure component and a fibre structure component have been reported by Chang(3). Chang studied one-sided dewatering and measured the hydraulic pressure at the impermeable bottom plate. He was apparently the first to measure the hydraulic pressure during dynamic compression of wet paper sheets.

Dynamic compression tests of wet paper sheets have also been performed by Asklöf et al.(4) and by Ceckler et al.(5). However, these investigators recorded only the compressive force and the thickness of the paper web during compression.

So far there have to our knowledge been no reports on the dewatering of wet fibre mats during a full loading cycle, that is in both the compression and the expansion phases.

This paper describes a servo-controlled hydraulic tester for studying the dynamic compression of saturated paper sheets. The apparatus can generate short press pulses of various shapes. The applied pressure, the hydraulic pressure and the thickness of the sheet are measured simultaneously during the pressing operation. The apparatus performs a full loading cycle which makes it possible to study both the compression and expansion phases.

The techniques for hydraulic pressure and sheet thickness measurement are also discussed.

Design and performance of the apparatus

Compression apparatus

The compression apparatus, figure 1, consists of a stationary solid brass bottom plate and a movable permeable top plate.

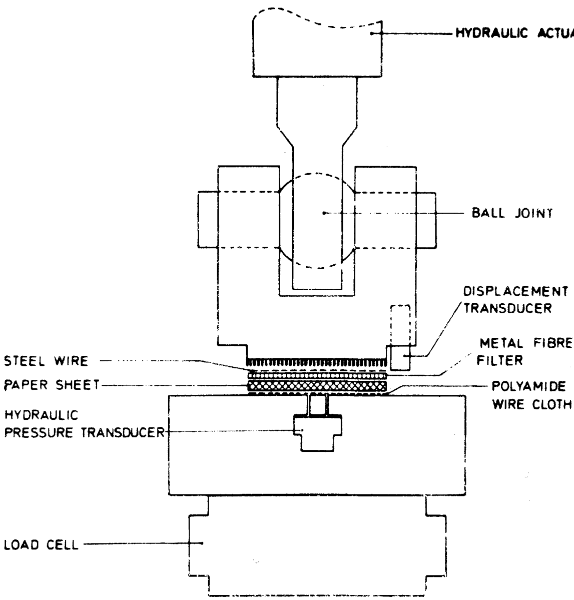

Fig 1

A thin polyamide wire is placed between the wet sheet and the bottom plate and a metal fibre filter and a stainless 100 mesh wire are inserted on the top of the sheet. The lower surface of the upper plate contains 0.7 mm wide grooves, which are 3 mm deep and are placed at intervals of 0.7 mm. The diameter of the top plate is 70 mm. The upper plate is connected to a hydraulic actuator via a ball joint. This joint ensures that the plates are parallel.

The metal fibre filter (N.V. Bekaert S.A., Metal Fibres Department, B. 8550 Zwevegem, Belgium) is used to achieve a uniform pressure distribution on the sheet. The filter provides structural rigidity combined with high permeability. The permeability factor for the filter is approximately 10 times greater than the permeability factor for an unbeaten bleached sulphate pulp, compared at a compressive pressure of 1 MPa.

The metal fibre filter has a total thickness of about 600 µm and the filter is compressed approximately 40 µm during a 1 MPa press pulse.

Instrumentation

The bottom plate is mounted on a 40 kN strain-gauge load cell whose accuracy is better than 0.5% of full load.

The hydraulic pressure on the bottom plate is monitored with a 10 MPa strain-gauge pressure transducer embedded in the bottom plate 8 mm beneath the surface and communicating with it by four holes. The diameter of each hole is 0.7mm, except where otherwise stated. The volume between the pressure sensitive surface of the transducer and the bottom plate is made as small as possible (less than 60 mm^3). The accuracy of the pressure transducer is better than 0.5% of full range.

An eddy current displacement transducer is mounted in the upper plate to measure the distance between the two plates. The displacement transducer has an operating range of 1.27 mm and an accuracy better than 0.4% of full range.

Servo-hydraulic system

The motion of the upper press plate is controlled by a servo-hydraulic testing system (MTS Systems GmbH, Potsdamer Str. 23/24, 1000 Berlin, West Germany). The system consists of a hydraulic actuator and a servo-valve mounted in a two-column load frame. The control system consists of a minicomputer (PDP 11/04) with a segment generator which allows the computer to generate complex waveforms by defining the end levels and frequencies of either ramp or haversine segments (haversine ωt = 1/2(1-cos ωt). The highest feasible frequency for the system is 200 Hz, that is a sine-press pulse with a length of 5 ms. The system also allows simultaneous reading and data monitoring from 3 channels with no time skew between the channels. The signals from the three transducers are sampled at a constant time interval of 0.3 ms. System input and output are implemented through a graphics terminal and a push-button panel. The raw data can be stored on floppy disks for subsequent calculations.

Experimental procedure

All tests were made with never-compressed sheets, which means that only the first compression-recovery cycle was recorded.

Before a sheet was placed on the bottom plate, the holes leading down to the pressure transducer and the space above it were filled with oil. Care was taken to remove air bubbles inside the liquid volume connecting the pressure transducer with the sheet.

Preliminary tests were made with both deaerated and non-deaerated sheets. As identical hydraulic signals were recorded in both cases, deaeration was not considered to be necessary.

Before each press test a calibration run is made without any sheet. The compression of the polyamide wire, the metal fibre filter and the steel wire is thus recorded and stored in the computer. A polyamide wire with 45 µm filaments and a filter with 12 µm fibres were used in all experiments unless otherwise stated.

Before the press pulse is applied, the sheet is precompressed to an initial dryness level of 25%. The upper plate is lowered over a period of 30 s to a predetermined distance from the lower plate, the distance being calculated as described below to correspond to the chosen moisture ratio.

After the press pulse has been executed a small compression is maintained on the sheet. The recovery of the sheet against this compression is thus monitored. In the experiments reported here this pressure was 0.038 MPa unless otherwise stated.

The thickness of the sheet is calculated as the difference between the recorded thickness in the actual run and that in the calibration run. The estimated error of the thickness measurement is within ±15 μm. Assuming saturated sheets and that there is no volume contraction or expansion during the mixing of cellulose and water, it is possible to calculate the solids content of the sheet from its thickness and the densities of fibres and water. The density of the dry bleached sulphate pulp was determined to be 1.55g/cm^3 in a density gradient column (Davenport Ltd., Welwyn Garden City, Herts, U.K.).

Standard tests

The results from a haversine press pulse are shown in figure 2. Total applied load, hydraulic pressure and solids content are given during the course of compression and expansion. The length of the press pulse is 25 ms. The maximum solids content is reached after 19 ms, i.e. in the later part of the expanding nip. The expanding sheet creates a negative hydraulic pressure after the press pulse which causes water flow back into the sheet.

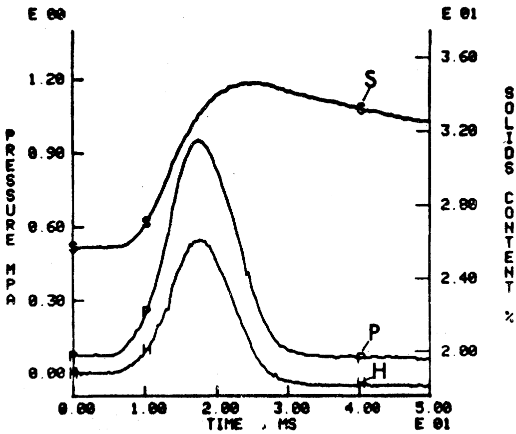

Fig 2

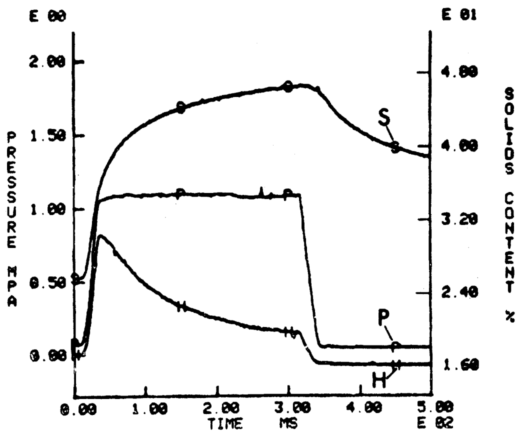

Fig 3

Fig. 3 shows the results from a square wave pulse. The load is increased on the sheet in 25 ms and maintained for a period of 300 ms after which the sheet is unloaded in 25 ms. The solids content increases throughout the whole press period. The compression generates a hydraulic pressure which continuously decreases from a maxiumum value obtained in the early part of the press pulse.

Technique for hydraulic pressure measurement

The initial experiments performed with the pressing apparatus often gave the result that the hydraulic pressure signal exceeded the total applied pressure for highly beaten pulps. This behaviour was always experienced after the maximum pressure in the press pulse. Such a result can be explained if the fibre mat clogs the holes connecting the surface of the bottom plate with the pressure transducer. Thus, during the compression phase the liquid in the transducer cell is compressed, but when the pressure is released, the fibres clogging the holes hinder the escape of liquid from the hydraulic pressure cell. When a polyamide wire was placed between the bottom plate and the wet fibre mat this tendency for the hydraulic pressure signal to exceed the total applied pressure signal was eliminated. It was thus considered important to check the influence of the mesh size of the chosen polyamide wire on the hydraulic pressure signal.

Figure 4 shows that the hydraulic signals are not influenced by the mesh size of the polyamide wire, but that a different hydraulic signal is obtained if the experiment is performed without polyamide wire.

In order to examine whether the size of the holes communicating with the pressure transducer had any influence on the hydraulic signal, tests were performed with holes of different diameters. Hole diameters of 0.4, 0.7, and 1.0 mm were tested. Table 1 shows that no significant differences in hydraulic pressure are recorded when the hole diameter is changed.

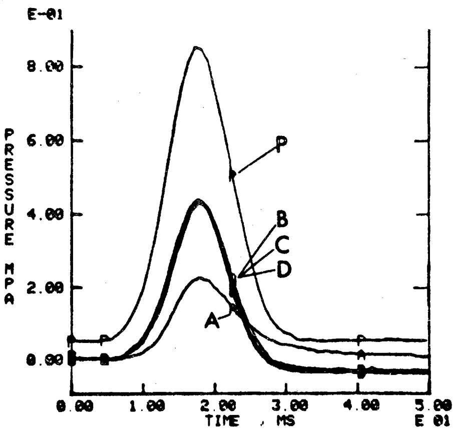

Fig 4

In the experiments performed by Chang(3), no anomalous behaviour of the hydraulic pressure signal could be noted as he only studied the compression mode. Our experiments therefore cast some doubt on the results reported by Chang.

Tests were made to examine whether there is any interaction between the metal fibre filter and the sheet. Changing the mesh of the filters above the sheet gave rise to no significant differences in hydraulic pressure signals. Table 2 gives the maximum hydraulic pressure recorded during identical press pulses with different metal fibre filters. Tables 1 and 2 also illustrate the natural scatter in the data.

Sheets with two different diameters (50mm and 70mm) were also tested and it was found that the area of the sheet has no effect on the hydraulic pressure recorded.

Pulp	Maximum hydraulic pressure, MPa		
	Diameter of holes		
	0.4 mm	0.7 mm	1.0 mm
Unbeaten	0.22	0.21	0.17
2,000 PFI-rev.	0.62	0.52	0.57
10,000 PFI-rev.	0.67	0.79	0.74

Table 1.
Maximum hydraulic pressure during a press pulse. Different diameters of the holes communicating with the pressure transducer. Bleached sulphate pulp. Grammage = 150 g/m^2. Press pulse time = 25 ms. Maximum applied load = 1 MPa. Metal fibre filter = 22 µm. Polyamide wire = 71 µm.

Diameter of steel fibres from which the metal filter is manufactured	Maximum hydraulic pressure	Minimum thickness of Sheet
µm	MPa	µm
4	0.49	356
8	0.51	316
12	0.53	312
22	0.52	350

Table 2
Maximum hydraulic pressure and minimum thickness of sheets during a press pulse with different metal fibre filters. Bleached sulphate pulp beaten to 2,000 PFI-revs. Press pulse time = 25 ms. Maximum applied load = 1 MPa. Grammage = 150 g/m^2. Mesh of polyamide wire = 71 µm.

Technique for thickness measurement

The influence of different metal fibre filters on the thickness measurements is shown in table 2. The thickness variations are not considered to be significant.

Different diameters of the sheets gave rise to no differences in the thickness measurement.

The sheet recovery is naturally dependent on the compressive force maintained on the sheet after the press phase. In figure 5 the recovery of sheets which are allowed to expand against different pressures is shown. The recovery increases with decreasing compressive force. The sheet reaches a maximum solids content of approximately 40% in the nip. Then the sheet expands and water is sucked back. In this example, the solids content decreases 5 to 10% depending on the compressive force applied during the expansion period of about 80 ms.

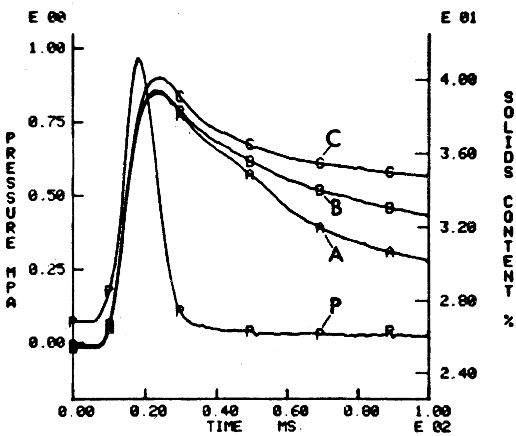

Fig 5

Typical results

In order to demonstrate further that the apparatus gives reasonable and reliable results we give some data from tests on sheets of different grammages and different degrees of beating.

Influence of grammage

Figures 6, 7 and 8 show how the generated hydraulic pressure, the solids content graphs and maximum obtained solids content in the nip depend on the grammage. The hydraulic pressure generated increases with increasing grammage.

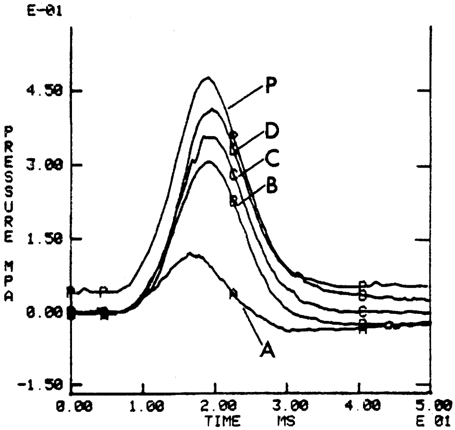

Fig 6

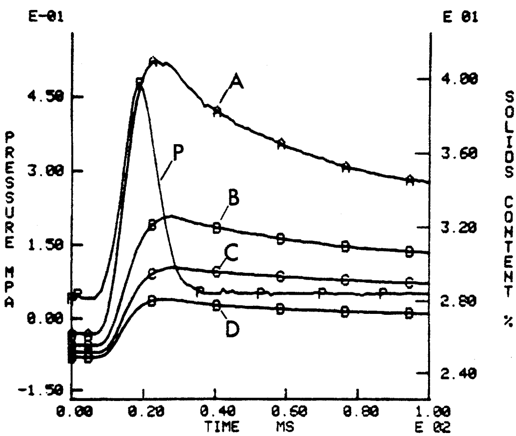

Fig 7

In figure 8 the maximum obtained solids content in the press nip is plotted against applied load. The 75g/m^2 sheet is the most sensitive to increasing pressure and reaches 50 % dryness at a load of 4 MPa.

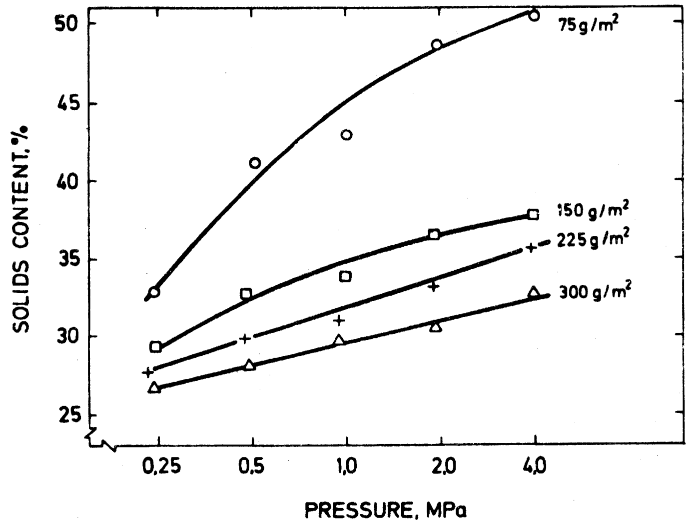

Fig 8

Figure 9 exemplifies the effect of pressure and time on the maximum dryness achieved in the press nip by the 150g/m^2 sheet. Increasing the nip residence time increases the solids content reached under the conditions in question.

Influence of beating

Figures 10, 11 and 12 show how the degree of beating influences the recorded press characteristics. The high resistance for water flow in a beaten pulp results in a higher hydraulic pressure and subsequently in a lower dryness. An unbeaten pulp is more sensitive to nip pressure and figure 12 illustrates how an unbeaten pulp has a steeper dryness-pressure relation than the beaten pulps.

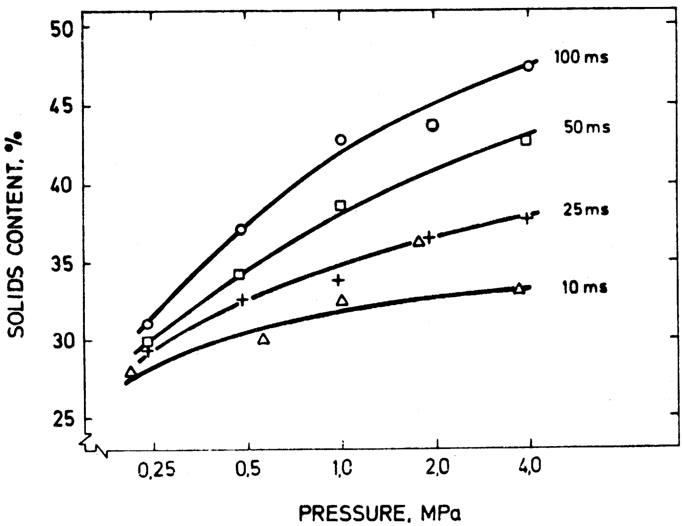

Fig 9

The compression recovery characteristics of the wet sheet may be described by the visco-elastic properties of the fibres and by the flow resistance of the structure. Thus dewatering can be characterised as flow-controlled or compression-controlled. Under flow-controlled conditions, a prolonged compression time is beneficial. All experiments reported here are mainly flow-controlled since a hydraulic pressure is recorded and an extended compression time has a positive effect. In the recovery phase the sheet structure expands and thus creates a negative hydraulic pressure. A less beaten pulp and a pulp of low basis weight have a lower flow resistance and water can more easily be sucked back into the sheet. Figs. 7 and 11 show a faster expansion for these sheets. Fig. 11 also shows how a certain combination of beating degree, pressure and time can result in an unbeaten pulp having a lower solids content than a beaten pulp after the nip, because of the faster expansion of the unbeaten pulp.

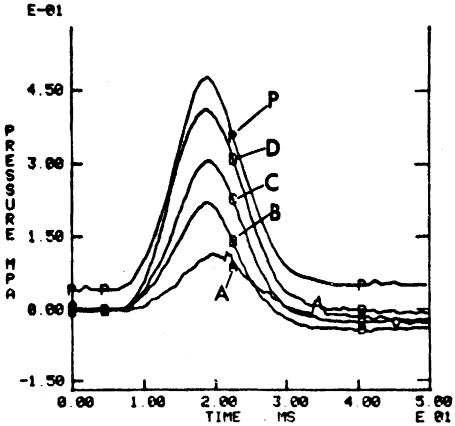

Fig 10

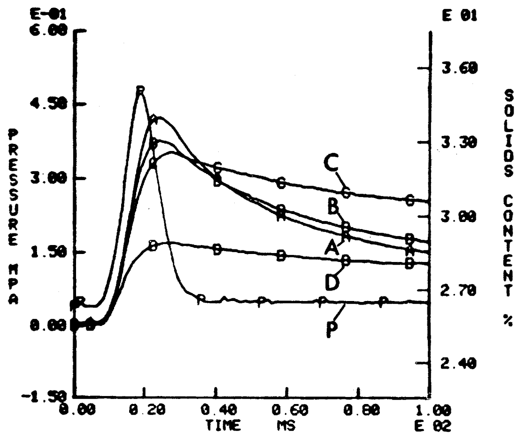

Fig 11

Preparation of sheets

The pulp used was a commercially manufactured never-dried bleached sulphate pulp from pine. The pulp was beaten in a PFI-mill according to standard methods[6]. The pulps were tested for water retention value (3000 g, 15 min)[7] and Schopper-Riegler (°SR), see table 3.

Pulp	°SR	WRV g H_2O/100 g pulp
Unbeaten	10	153
1,000 PFI-rev	15	162
2,000 PFI-rev	16	167
3,000 PFI-rev	17	173
10,000 PFI-rev	33	189

Table 3.
Drainability (°SR) and water retention values (WRV) of the pulps used.

Tap water was used during pulp preparation and sheet forming.

Sheets with different basis weights were made on a dynamic sheet former (Formette Dynamique, CTP, France). Circular samples punched from the fresh, unpressed sheet were kept saturated until needed for testing.

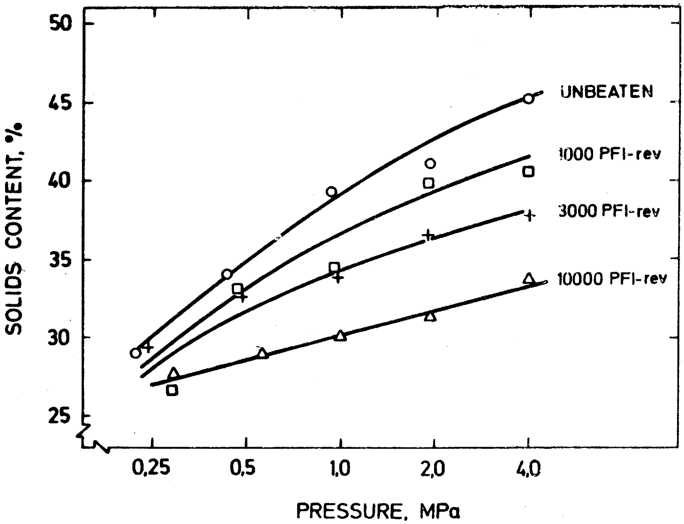

Fig 12

Acknowledgements

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The authors are indebted to Mr Petter Kolseth at this laboratory for valuable support and criticism during the course of this work.

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Transcription of Discussion

Discussion following paper given by Mr. G. Carlsson

Prof. K.I. Ebeling, Helsinki University of Technology, Finland

In the tests where you used very high pressure pulses, did the sheet tend to explode at the periphery? You measured the hydraulic pressure only at the centre, so do you have any information about the conditions at the peripheries of the sheets. Did the fibres fly apart, and was there any indication of lateral flow?

Mr. G. Carlsson, STFI, Sweden

The paper only exploded sideways when it was very wet. Under normal circumstances that wasn't a problem. On the question of uniformity of the pressure distribution, and lateral flow, we found by experimenting with sheets of differing diameters that sheet area had no effect on the hydraulic pressure recorded, or on the measured solids content. Thus we concluded that lateral flow was negligible.

Mr. A. Ibrahim, AccuRay, USA

You mentioned that at low basis weight a free sheet will show low flow resistance so that water is easily sucked back into the sheet after the pressure pulse. Do you think this conclusion is valid on a paper machine, where the sheet is backed by a felt, and where capillary action can take place? Here I would expect a free sheet to suck back less water than in your experiment because of the capillary action between sheet and felt. In other words, water will rise higher in smaller diameter pores than in larger, in the presence of a felt.

To recapitulate therefore, while on the basis of your result, it is true to say that the lower flow resistance of less beaten stock will allow water to be sucked back more readily after the pressure pulse, I believe that on a paper machine, the capillary action between sheet and felt will ensure the reverse.