On the Role of Evaporation Processes During Impulse Pressing of Paper

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“As the poet said, Only God can make a tree — probably because it’s so hard to figure out how to get the bark on.”

(Woody Allen)

“The greatest lesson in life is to know that even fools are right sometimes.”

(Sir Winston Churchill)
Abstract

Impulse technology is a process in which water is removed from a wet paper web by the combined action of mechanical pressure and intense heat. The press nip where this occurs is formed between a hot rotating press roll and a press shoe. The shape and loading conditions of the press shoe determine the applied pressure profile. This process results in increased dewatering rates, increased smoothness on the roll-side of the sheet, and increased density. Although the literature is rich of speculative attempts to clarify the mechanisms of an impulse event, a complete assessment of the physics of the process is still missing. The most fundamental issue on the matter is how the water is transported within and away from the sheet.

This thesis presents the main results of a laboratory investigation of the mode of dewatering of wet paper webs during an impulse pressing event. We tried to study this issue by two independent sets of experiments performed on a laboratory press simulator. We measured the internal temperature profile during impulse pressing of softwood bleached kraft (SBK) sheets of grammage ranging up to 300 g/m$^2$. The initial dryness of the samples was approximately 30 weight percent. Moreover, we investigated the energy efficiency of impulse technology by comparing the total heat transferred to a wet sample with the theoretical evaporation energy needed to dry all water not removed by traditional wet pressing. We performed heat flux measurements on sheets with grammage 20 g/m$^2$, 60 g/m$^2$, 120 g/m$^2$ and 300 g/m$^2$ pressed with a 20 ms extended pulse. The temperature of the press was ranging from 23°C to 300°C.

We found indications that a displacement dewatering mechanism can assist wet pressing and evaporative drying in accounting for the high dewatering rates observed during impulse pressing of paper. Yet, this mechanism seems to be grammage dependent and we found that a minimum basis weight of approximately 120 g/m$^2$ is required for its existence. We propose that this kind of “impulse effect” should be interpreted as an example of the “flashing-assisted displacement dewatering” originally proposed by Lucisano (2000).

Additionally we tested a patented solution to prevent or repair delamination in connection to impulse pressing of wet paper. It is proposed that the use of multiple press pulses with carefully controlled profile should be effective in this respect. The results of our measurements clearly show that paper samples are exposed to an internal expanding force even after five consecutive pulses.
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Chapter 1

Background

The forest industry is the largest contributor to the Swedish net export according to Swedish statistics ((Swedish Forest Industries Federation, 2001)). The

![Graph showing Swedish export balance in 1998 for different industrial sectors](source: Statistics Sweden)

Figure 1.1: Swedish export balance in 1998 for some different industrial sectors (Swedish Forest Industries Federation, 2001).

surplus was 75 billion SEK in the year 1998 and the export value of the Swedish
Now, we know that the pulp and paper industry is important for the Swedish economy. But paper, what is that? Everyone uses it on a daily basis. The newspaper you read together with your breakfast in the morning, the paper you use to clean up the milk you spilled out at the same breakfast (and the milk package itself). And possibly the most evident example: my thesis you are reading right now!

Paper was invented according to Chinese history in 105 A.C. by the minister Ts’ai L Lun. He used bark, hemp, rags and fishing nets as raw materials. Today, paper is made mainly of wood fibres; that is well known. But the rest then? One simple answer could be that trees are cut down, and the bark is stripped of. Trees are then cut into pieces, which are ground to very small sizes. The single fibres in wood chips must be separated further to be suitable for sheet forming. There are mainly two ways of accomplishing that: mechanically by grinding the wood chips, or chemically by cooking the chips with chemicals. When the wood is cooked and treated chemically, lignin, a substance that acts as a glue in native wood, is dissolved from the fibre material. When this “glue” is removed, wood fibres do not hold together any more and can be suspended in water. By means of dilution with large quantities of water, fiber aggregation is prevented.

Now we have reached the papermachine, which can be seen as an enormous machine to remove water from the fibres (Figure 1.2). The papermachine can be divided into three sections. The first section is the wire section. Here, the water-fibre mix is sprayed out over a wire. The purpose of the wire is similar to a filter: it allows the fibres to consolidate, whereas water is free to pass through it. Although almost all the water leaves the fibre mix through the wire, there still too much water left in the sheet. In the press section, water is pressed out between two press rolls in a machine that is similar to a mangle. In the last section, known as the drying section, the remaining water is evaporated by letting the web come in contact with a large number of steam-heated rolls.

The drying process is a massive energy consumer: two thirds of the total energy consumption for the paper machine is consumed in this section (McConnell, 1980). Moreover, Figure 1.3 illustrates how the mass of water removed in the dryer section is very moderate compared to the total dewatering capacity of an entire papermachine. Furthermore, investment costs are proportional to
the number of cylinders needed (sometimes more than 120 cylinders). Reducing the number of cylinders would mean substantial savings in capital costs. Therefore, great efforts have been put into minimizing and optimizing the dryer section, since even a small improvement of the process can lead to lower capital and operational costs. Yet another area rich in development is the press section. Here, higher dewatering rates can be achieved using a somewhat new web consolidation process: impulse technology.
Figure 1.3: Water removal in a Fourdriner papermachine (Krook et al., 1996)
Chapter 2

Impulse Technology

2.1 Introduction

Impulse technology is a novel web consolidation technique aimed at decreasing the investment costs and lowering the operational costs of a papermachine. In its present form, the process is a direct evolution of the idea originally proposed by Wahren (1978) and later named “Impulse Drying” (Arenander & Wahren, 1983): the wet pressing and drying operations can be combined into a single event by pressing the sheet in a nip formed between a felt-covered shoe and a solid roll. The latter is heated externally to temperatures exceeding 200°C. For a general review of the topic see for example Stenström (1989), Persson (1994), Nilsson (1998) and van Lieshout (1999) and the references contained therein.

Although impulse pressing of paper uses high-grade energy for dewatering the sheet, it has generally been postulated to be economically advantageous since:

(1) it uses less energy than conventional drying because all water may not need to be evaporated;

(2) it permits substantially higher speeds and drying rates than conventional design;

(3) it eliminates or strongly reduces capital costs for bulky drier sections, and associated peripheral equipment.
2.2 Wet Pressing and Impulse Technology

Impulse pressing of paper is similar in nature and mode of operation to traditional wet pressing technologies. Yet, its characteristic feature is the simultaneous action of intense thermal energy and mechanical pressure. This results in increased smoothness on the roll-side of the sheet (Burton et al., 1986; Lavery, 1987, 1988) and decreased bulk (Sprague & Burton, 1986; Lavery, 1987). Moreover, the specific energy consumption\textsuperscript{1} for drainage in excess of traditional wet pressing operation has been reported to be lower in impulse pressing than that in classic drying operations (e.g. Devlin, 1986; Larsson, 1999; Nilsson, 2001).

The dramatic increase in heat flux and water removal rate experienced with impulse drying suggests that the mechanisms that control dewatering differ significantly from those of conventional pressing and drying operations. Results from the aforementioned experimental studies suggest that additional mechanisms are responsible for a major portion of the water removed from the sheet. We will refer to any non-traditional dewatering mechanism occurring in connection with an impulse event as “impulse effect”. An analysis of the literature published in the field shows that all investigated hypotheses can be summarized in three main classes:

1. Steam-assisted displacement dewatering;
2. Temperature related effects on liquid dewatering;
3. Flashing-induced dewatering.

The following sections present these three mechanisms in more details.

2.3 Steam-Assisted Displacement Dewatering

The physics of an impulse event are more complex than just the superposition of wet pressing and evaporative drying and the existence of additional dewatering mechanisms has been postulated. According to the original description of the

\textsuperscript{1}We define the specific energy consumption as the total energy needed to dewater a unit mass of water, disregarding the mode of drainage.
Figure 2.1: Steam-assisted water displacement (Rigdahl et al., 1999): an idealized steam front expels part of the water in the compressed paper web during the impulse process. This additional mechanism is assumed to remove water in the liquid phase, therefore accounting for the high energy efficiency of impulse technology.

In impulse event, steam is formed in the first part of the press nip as soon as the sheet comes in contact with the heated roll (Wahren, 1978). The resulting steam pressure is expected to act as an extra press force, thus displacing liquid water from the wet sheet into the felt (Figure 2.1). Additionally, the heat transfer between the steam, the fibers and the water remaining in liquid phase is assumed to be so effective that an efficient heat-up of the sheet is obtained with little energy losses. In the literature, this theory is referred to as “Steam-assisted displacement dewatering” (Wahren, 1982; Arenander & Wahren, 1983; Orloff et al., 1998b; Lindsay, 1989).

Arenander & Wahren (1983), Devlin (1986) and Rudemiller (1989) report indications that such a vapor-phase displacement mechanism drives water from the sheet due to volume expansion upon phase change.
2.4 Temperature Effects on Dewatering

Whereas the significance of the steam pulse as an explanation to the very high dewatering rates found in impulse drying has been discussed above, there are other concurrent effects which most certainly contribute to increase dewatering in a wet web which is subjected to intense heat during mechanical compression. The viscosity and the surface tension of water are lower at higher temperatures, which leads to an overall reduced flow resistance in the fibre network (Wahren, 1982; Arenander & Wahren, 1983; Back, 1991). The reduced surface tension also reduces the rewet caused by capillary suction. Furthermore, increasing the web temperature above the glass transition temperature of lignin and of the other wood polymers causes softening of the web. Web compressibility is thereby significantly increased. Krook et al. (1996) showed that an increase of temperature is accompanied by a significant increase in compressibility and thereby dewatering in both mechanical and chemical pulps, the increase being most significant between room temperature and 100°C (Figure 2.2).

![Figure 2.2: Minimum pressing thickness as a function of hot surface temperature for 80 g/m² sheets of different pulps: TMP = thermomechanical pulp, ub = unbleached kraft, b = bleached kraft. (Krook et al., 1996).](image-url)
2.5 Flashing-Induced Dewatering

A third type of phenomena occurring in connection to an impulse event is related to the processes taking place upon unloading of the paper web. Indeed, Macklem & Pulkowski (1988) proposed that impulse pressing can be interpreted as a combination of wet pressing (taking place in the nip) and rapid flashing evaporation, occurring when the mechanical load is released. According to this interpretation, all or most of the water trapped in the paper web remains in liquid phase in the press nip, in spite of the high temperatures recorded in direct experiments. This is possible because of the high hydrodynamical pressures generated during the rapid mechanical loading of the wet web (Campbell (1947), Wahlström (1960a, b, 1969) and Nilsson & Larsson (1968)). Yet, a violent and almost explosive generation of steam is expected to take place as soon as the web leaves the nip and pressure is brought back to atmospheric conditions.

Indeed, impulse pressing, as originally proposed by Wahren, can be interpreted in the light of a patent describing a continuous process for expanding fibrous materials such as paper, tobacco and cotton (van Tilburg, 1975). In

![Figure 2.3: Comparison between the apparatuses patented by van Tilburg (1975) (left figure) and Wahren (1978) (right figure).](image)

the process described in the patent claims, heat and mechanical pressure are applied to a system of a porous material together with an expanding or puffing agent, such as liquid water. This causes the expanding agent to reach temperatures above its atmospheric saturation point. When the applied pressure
is released, the puffing agent flashes to steam and expands, thereby causing a volume increase in the porous material. The two apparatuses patented by Wahren and van Tilburg are illustrated in Figure 2.3, whereby the similarity of the two suggested solutions appears striking. These two patents would show a complete agreement if an expanding phenomenon was present within impulse technology. Indeed, the most serious runnability problem encountered both in laboratory scale simulations and in pilot scale applications of impulse technology is delamination Figure 2.4, which is defined as a drastic reduction in the z-directional strength of the paper (Crouse & Woo, 1989; Orloff et al., 1998b; Orloff & Crouse, 1999; Larsson & Stenström, 1998).

Figure 2.4: The left figure shows the surface of a impulse pressed sheet with a delamination blister in the center (Picture courtesy of Narcis Mesic, STFI). The right picture reports a cross-section of a delaminated sheet, showing a porous domain that divides the sheet in two layers. Fibres in the upper left corner of the picture are oriented vertically instead of horizontally. The orientation of these fibers, together with that the fact that the sheet is delaminated, indicates that the force dissipated by the steam flow exceeded the z-directional strength of the web (Lucisano, 2000).

It is generally accepted that delamination occurs when the force dissipated by the flow of steam is greater than the z-directional strength of the wet web and that the steam responsible for delamination is generated upon unloading of the nip (van Tilburg, 1975; Crouse & Woo, 1989). Further, this description is supported by the only direct experimental attempt to investigate the physical state of water during an impulse event (Zavaglia & Lindsay, 1989). They found that no or insignificantly little steam forms before maximum load because the pressure exceeds water’s vaporization temperature (Figure 2.5). But when the
pressure is released, the water temperature is well above the atmospheric evaporation temperature. This results in an instantaneous phase change, i.e. the water flashes to steam, thereby delaminating the sheet.

Figure 2.5: Picture taken with a flash x-ray camera 13 ms in an impulse with at well time of 14 ms. A tracer, present in the liquid phase only, added at top of the sheet in order to spot steam. In all pictures, the dark part in the top of the picture is the platen press head. The upper part of the bright region is the sheet lying against a press felt. The dark region under the felt is a supporting material. In picture B the tracer has been added, which appears on the x-ray picture as a dark spot. There is no brighter region in the paper above the darker liquid region, which agrees with the commonly accepted description of traditional wet pressing. A brighter spot directly above the darker region can be seen in picture C. This can be interpreted as steam (Zavaglia & Lindsay, 1989).

In a recent work, Lucisano (2000) utilized a series of laboratory pressing experiments to study the mechanism of heat transfer with phase change during impulse pressing of paper. They could not find any evidence of the steam-assisted displacement mechanism suggested by Wahren (1978) in the initial portion of the nip. Yet, they identified a strong increase in the internal temperature of the sheet taking place upon unloading the web (Figure 2.6). They interpreted their
results as a displacement dewatering mechanism similar to the one postulated by Wahren (1978) with the difference that the driving force they identified was provided by the expansion of flashing water. To the knowledge of the author, this is to be considered as the first direct indication that displacement dewatering can exist in connection with impulse pressing of paper. Therefore, the mechanism proposed by Lucisano (2000) can be referred to as “flashing-assisted water displacement”. Unfortunately, their conclusions were drawn on the basis of extremely simplified model experiments, and their validity should be tested in conditions closer to the industrially relevant processes.

Figure 2.6: Internal web temperatures during impulse pressing of SBK hand-sheets on a laboratory platen press. The hot plate temperature was set to 300°C, the peak pressure was 8.4 MPa, the total grammage was 500 g/m² and the length of the pressure pulse was approximately 120 ms (Lucisano, 2000). A sudden increase in temperature when the mechanical load was released from the paper sample with platen temperatures higher than 200°C and compression times smaller than 500 ms.

The main experimental conditions that should be modified in order to obtain a more realistic results can be listed in the following points:

(i) pressing experiments were position controlled instead of load controlled;
(ii) the pressing time was too long, ranging from 100 ms to 15 s;
(iii) the paper samples had the uncommonly high grammage of 500 g/m²;
(iv) the pulse shape was triangular.
If the explanation proposed by Lucisano (2000) proves to be correct even for impulse pressing in full scale installations, its application would prove to be very interesting in connection with a patented solution to the paper delamination problem (Figure 2.7). In fact, Vomhoff (2000) claims that paper sheets that delaminate during the first of a series of multiple press pulses can be repaired when pressed again. Multiple press pulses should thereby heal the web damage. Unfortunately, no experimental results have been published to test this simple but however ingenious solution to repair delamination damages.

Summarizing, the so far unsolved problem with impulse technology is that the sheets delaminate after the pressing event, if the operating conditions fall outside of the runnability range. Under the assumption that the “steam assisted
water displacement” theory is correct, attempts have been made to parameter regulate the pressing to absent delamination (see for example Orloff, 1991, 1992; Orloff & Lindsay, 1992; Orloff et al., 1992; Orloff & Sobczynski, 1993; Orloff & Lenling, 1993; Orloff, 1994; Orloff et al., 1997b,b,a, 1998b,c,a; Orloff & Crouse, 1999). If flashing exists and plays an important part in the physics of impulse pressing, which there are proof of, the reality is different. Expanding steam can be expected to escape from the sheet the easiest way, when the pressure is released. That is apparently out from the sheet rather then through the sheet. The consequence is quite apparent and is to be spelled: DELAMINATION.

2.6 Summary of the Literature

The mystery behind “impulse technology” has not been solved despite more than two decades of active research. Although the literature is rich of speculative attempts to clarify the mechanisms of an impulse event, a complete assessment of the physics of the process is still missing. The most fundamental issue on the matter is how the water is transported within and away from the sheet. In summary:

(i) Impulse technology is a web consolidation process in which water is removed from wet paper by the combined action of mechanical pressure and intense heat.

(ii) There is a large body of information available in the literature on the changes in paper property and increases in dewatering rates produced by impulse pressing. From this, the mechanism by which steam is formed has been inferred. Few of these works specifically address the central issue of this thesis, that being, to experimentally characterize the role of steam forming processes in connection with impulse pressing of wet paper webs.

2.7 Objectives

The aim with this thesis is to establish whether impulse technology is governed by a pressing/flashing phenomenon rather than by a displacement mechanism.
Chapter 3

Experimental

3.1 Platen Press and Sample Preparation

All the experiments reported in this study were performed on a platen press from Material Testing Systems (MTS) earlier described by e.g. Krook et al. (1996) and Rättö & Rigdahl (1998). The platen press consists of a heated press head connected to a data-acquisition system that records the press load with a 40 kN load cell and the position of the head (Figure 3.1). The top pressing plate is a solid block of SS1914 steel with embedded electrical heaters, allowing for surface temperatures in excess of 300°C. Table 3.1 reports the thermal properties of SS1914 at 100°C (Krook & Stenström, 1998). One fast responding thermocouple from Nanmac Corp. is installed and integrated in the surface of the press head. The time constant for the surface thermocouple is reported to be lower than 10 µs (Krook & Stenström, 1998). The surface thermocouple is connected to the aforementioned data acquisition system.

Experiments were performed in a conditioned room at a temperature of 23°C and 50 percent relative humidity. Finnish handsheets with grammage of 20 g/m², 60 g/m², 120 g/m² and 200 g/m² were made on a Finnish web former with an open white water system from a softwood bleached kraft (SBK) pulp beaten in a PFI-mill to approximately 15°SR (1700 revolutions). Sheets were then gently pressed between blotters to a dryness of approximately 30 weight percent. Four circular samples with a diameter of 79 mm were punched from
Table 3.1: Physical properties of SS1914 (Krook & Stenström, 1998).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>(k_l(T = 100^\circ C))</td>
<td>60</td>
<td>W/m·K</td>
</tr>
<tr>
<td>(\rho_l(T = 100^\circ C))</td>
<td>7800</td>
<td>kg/m³</td>
</tr>
<tr>
<td>(c_{p,l}(T = 100^\circ C))</td>
<td>480</td>
<td>J/kg·K</td>
</tr>
</tbody>
</table>

Each handsheet and stored in plastic bags at 4\(^\circ\)C until pressing. Prior to the experiment, an appropriate number of these samples were couched together to create a paper web with the desired grammage.

Figure 3.1: Schematic of the MTS platen press and the pressing head (Krook et al., 1996)

The pre- and post-nip dryness of each sample was determined by weighting the sheet directly before and after each pressing event. After pressing, samples were dried in a 105\(^\circ\)C warm air oven, before their dry weight (and thereby their grammage) was measured. The dryness increase upon pressing will be given as change in moisture ratios, \(MR_{in} - MR_{out}\); where the moisture ratio is defined as the ratio of the mass of water to the mass of dry fibers in the sheet.
3.2 Measurements of the Internal Sheet Temperature Profile

Temperature measurements were performed by embedding type E microthermocouples (Omega Engineering Inc.) between the individual layers of the paper web. In total, between three and eight thermocouples were embedded at different elevations through the paper web, as illustrated in Figure (3.2A). The time constant for the microthermocouples was lower than 2 ms. The temperature signals were recorded with a sampling frequency of 1 kHz on the data acquisition system described in details by Rättö & Rigdahl (1998).

The thermocouples were approximately 25 µm in diameter and were considered small in comparison to the thickness of the compressed paper samples; they are however of the same order of magnitude of the fibres (Figure 3.2B). The thermocouples were not located at the same radial position at each elevation of the paper sample, but rather positioned in the central portion of the sheet.

Figure 3.2: (A) Examples of sheet structure used for temperature profile measurement. The filled dots mark the position of the microthermocouples. (B) Micrograph of the thermocouple sampling point, on the background of a 20 g/m² sheet of the same kind used in the experiments.

Three different types of single press pulses were tested: triangular, Haversine and extended press pulse. Additionally, these pulses were combined in series of two to five consecutive pulses (Figure 3.3¹). A summary of the experimental

¹The position of the press head reported in Figure 3.3 is to be interpreted with extreme
conditions can be found in Table 3.2.

Table 3.2: Experimental conditions for the temperature profile measurements.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot plate temperature</td>
<td>°C</td>
<td>300</td>
</tr>
<tr>
<td>Maximum applied pressure</td>
<td>MPa</td>
<td>8</td>
</tr>
<tr>
<td>Single pulse length</td>
<td>ms</td>
<td>12-300</td>
</tr>
<tr>
<td>Total grammage</td>
<td>g/m²</td>
<td>100-500</td>
</tr>
<tr>
<td>Initial sheet dryness</td>
<td>weight percent</td>
<td>30</td>
</tr>
<tr>
<td>Pulse shape</td>
<td></td>
<td>Triangular (Position Controlled)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extended Nip (Load Controlled)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Haversine (Load Controlled)</td>
</tr>
<tr>
<td>Number of consecutive pulses</td>
<td></td>
<td>1-5</td>
</tr>
<tr>
<td>Backing material</td>
<td></td>
<td>glass sintered plate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>pressing felt</td>
</tr>
</tbody>
</table>

3.3 Heat Flux Measurement

During heat flux trials, no thermocouples were embedded in the paper samples, but the surface temperature of the platen press head was recorded with a sampling frequency of 1 kHz. The temperature history of the press plate was then used to calculate the heat flux out of the press head (Figure 3.4). The method is based on the solution of the heat conduction problem in the hot pressing plate modelled as a one-dimensional, semi-infinite medium with a step change in surface temperature (Carslaw & Jaeger, 1959). A discussion of the applicability of the semi-infinite body assumption to STFI:s platen press is presented in Krook (1996).

Under the assumption that the density, \( \rho \), specific heat capacity, \( c_p \), and thermal conductivity, \( k \), of the solid metal block can be considered constant with care. Since a pressing felt was used as backing material in most of the experiments, the position signal cannot be set in direct correlation with the thickness of the paper sample.
Figure 3.3: Example of pressure pulses used during the experiments (blue lines). The position of the press head (red lines) is reported for the convenience of the reader. The pulses used can be divided in four categories: (A) position controlled triangular pulses, (B) load controlled extended press pulses, (C) load controlled Haversine pulses, and (D) multiple press pulses obtained by the combination of two to five pulses of any of the previous types.
temperature, the non-stationary surface heat flux, $q_s = q_s(t)$, can be calculated using the following equation:

$$q_s(t) = \sqrt{k\rho c_p} \int_0^t \frac{1}{\sqrt{t-\Theta}} \frac{dT_s(\Theta)}{d\Theta} d\Theta,$$

(3.1)

where $T_s = T_s(t)$ is the measured instantaneous surface temperature and $\Theta$ is a dummy temperature variable.

The effect of inaccuracy in the surface temperature due to the measurement noise was reduced by applying a digital filter prior to using the numerical procedure for the solution of the inverse heat conduction problem suggested by Taler (1996). The numeric procedure proposed there was programmed in MATLAB® (Lucisano, 2001, see Appendix A). The total heat transported out of the press
head per unit contact area was calculated by integrating \( q_s = q_s(t) \) over the duration of the pulse pulse:

\[
Q = \int_{t_0}^{t_1} q_s(t) dt,
\]

(3.2)

where \( Q \) is the total heat per unit area conducted out of the hot plate during the press pulse and \( t_0 \) and \( t_1 \) are respectively the first and last instant of thermal contact between the hot press head and the paper sample. Heat flux trials were made using a extended pulse with a residence time of 20 ms with a maximum load of 8 MPa. Sheets with grammage of 20 g/m\(^2\), 60 g/m\(^2\), 120 g/m\(^2\) and 200 g/m\(^2\) were measured at pressing temperatures ranging from 23°C to 300°C. For the 20 g/m\(^2\) sheets, tests could only be performed up to 180°C because the supplied heat tended to melt the the supporting press felt. In all cases, samples were pressed against a pressing felt with initial dryness kept at approximately 30 weight percent. A summary of the experimental conditions used for the heat flux trials is presented in Table 3.3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Values</th>
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<tbody>
<tr>
<td>Hot plate temperature</td>
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<tr>
<td>Maximum applied pressure</td>
<td>MPa</td>
<td>8</td>
</tr>
<tr>
<td>Pulse length</td>
<td>ms</td>
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</tr>
<tr>
<td>Total grammage</td>
<td>g/m(^2)</td>
<td>20-200</td>
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<tr>
<td>Initial sheet dryness</td>
<td>weight percent</td>
<td>30</td>
</tr>
<tr>
<td>Pulse shape</td>
<td></td>
<td>Extended Nip (Load Controlled)</td>
</tr>
<tr>
<td>Backing material</td>
<td></td>
<td>pressing felt</td>
</tr>
<tr>
<td>Initial felt dryness</td>
<td>weight percent</td>
<td>30</td>
</tr>
</tbody>
</table>
Chapter 4

Results and Discussion

4.1 Assessment of Impulse Effects

Platen press experiments were used to investigate whether the combination of wet pressing and evaporative drying is sufficient to account for dewatering during impulse pressing of paper. In fact, non-traditional “impulse effects” such as steam-assisted displacement dewatering, flashing-induced dewatering and temperature related effects on liquid phase dewatering, have been postulated in the literature. Yet their importance for the overall mechanism of impulse pressing is still uncertain.

A heat balance over the process was used to study the relationship between the thermal energy transferred to the paper sample during the impulse and the energy theoretically needed to evaporate all water removed in excess of wet pressing. The total heat supplied by the hot press head was calculated from instantaneous measurements of the surface temperature of the press.

Each paper sample was weighed before and after the pressing event and after being dried in a oven heated to 105°C. Thereby the total amount of drained water could be calculated. Figure 4.1 presents the change in moisture ratio upon hot pressing (red points) and impulse pressing (blue points) of SBK paper samples of four different grammages: (A) 20 g/m², (B) 60 g/m², (C) 120 g/m² and (D) 200 g/m². Here, the moisture ratio, MR, is defined as the ratio of the
Figure 4.1: Change in moisture ratio as a function of the pressing temperature upon hot pressing (red points) and impulse pressing (blue points) of SBK paper samples. Experiments have been performed at (A) 20 g/m², (B) 60 g/m², (C) 120 g/m² and (D) 200 g/m². The moisture ratio prior to pressing was approximately 2.3. The wet pressing contribution is not excluded.
mass of water to the mass of dry fibers in the sheet. In total, approximately 300 pressing experiments were performed in this section of the work.

The net water removal due to heat related effects was calculated by subtracting dewatering by traditional wet pressing from the total removed water. For every grammage, dewatering by wet pressing was calculated from at least ten samples.

The theoretical energy needed to evaporate all drained water not removed by wet pressing was then calculated by setting up an energy balance on the fibers and water:

\[
Q_{ev} = w \cdot c_{p,f} \cdot \Delta T + w \cdot M_{R_{in}} \cdot (h_{l,\text{out}} - h_{l,\text{in}}) + w \cdot \left[ (-M_{R_{in}} + M_{R_{out}}) - (-M_{R_{in}} + M_{R_{out}})_{\text{wet}} \right] \cdot h_{ev},
\]

(4.1)

where \(Q_{ev}\) is the evaporation energy per unit sample area, \(\Delta T\) is the difference in sheet temperature before and after the nip, \(h_l\) is the enthalpy of liquid water, \(h_{ev}\) is the latent heat of evaporation of water, \(w\) is the basis weight of the sample, \(c_{p,f}\) is the specific heat of the fiber material and \(M_{R_{in}}\) and \(M_{R_{out}}\) are the moisture ratios of the paper sample before and after pressing, respectively. Additionally, the subscript \(\text{wet}\) indicates wet pressing conditions. Equation 4.1 is valid under the following assumptions:

(1) In the initial state, the sheet is at room temperature (23 °C), atmospheric pressure and it has moisture ratio \(M_{R_{in}}\).

(2) All water evaporation phenomena take place at 100 °C and atmospheric pressure.

(3) In the final state, the sheet temperature is 100 °C, its moisture ratio is \(M_{R_{out}}\) and pressure is atmospheric.

(4) All dewatering in excess of wet pressing \((M_{R_{out}} - M_{R_{in}})_{\text{wet}}\) takes place by evaporation.

Following from assumptions (1) \(\rightarrow\) (4), the numerical values of the parameters in Equation 4.1 are given in Table 4.1.

Figure 4.2 illustrates the results for SBK paper samples with grammage 20 g/m², 60 g/m², 120 g/m² and 200 g/m². Experiments were performed at pressing temperatures ranging from 23°C to 300°C, with two to four replications.
Table 4.1: Numerical values of the parameters in Equation Equation 4.1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Units</th>
<th>Source/Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c_{p,f} )</td>
<td>1340</td>
<td>J/kg · K</td>
<td>(Kerekes, 1980)</td>
</tr>
<tr>
<td>( \Delta T )</td>
<td>77</td>
<td>°C</td>
<td></td>
</tr>
<tr>
<td>( h_{ev} )</td>
<td>2.2567</td>
<td>MJ/kg</td>
<td>at 100 °C</td>
</tr>
<tr>
<td>( h_{l,in} )</td>
<td>105</td>
<td>kJ/kg</td>
<td>at 23 °C, 1 atm</td>
</tr>
<tr>
<td>( h_{l,out} )</td>
<td>417.5</td>
<td>kJ/kg</td>
<td>at 100 °C, 1 atm</td>
</tr>
</tbody>
</table>

Figure 4.2: Comparison between the heat supplied to the paper sample during impulse pressing of paper and the theoretical evaporation energy calculated with Equation Equation 4.1. Experiments have been performed at (A) 20 g/m², (B) 60 g/m², (C) 120 g/m² and (D) 200 g/m². The experimental points are relative to different pressing temperatures ranging up to 300 °C in all subplots except (A) where the maximum temperature was 180°C.
at every temperature. For the 20 g/m² sheets, tests could only be carried out up to 180°C because the intense heat tended to melt the the supporting press felt.

The slopes of the trend lines in Figure 4.2 provide information on the efficiency of the total impulse effect relative to traditional evaporative drying. Three cases are possible:

(i) A unitary slope corresponds to the case in which the supplied energy exactly matches the energy required to evaporate all water not removed by traditional wet pressing.

(ii) If the slope is larger than 1, more energy is supplied that what is strictly necessary to evaporate all water not removed by traditional wet pressing.

(iii) If the slope is lower than 1, the dewatering mechanism is more energy efficient than evaporative drying.

Table 4.2: Comparison between the energy supplied to the paper sample during impulse pressing of paper and the theoretical evaporation energy calculated with Equation Equation 4.1.

<table>
<thead>
<tr>
<th>Grammage [g/m²]</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1.1</td>
</tr>
<tr>
<td>60</td>
<td>1.1</td>
</tr>
<tr>
<td>120</td>
<td>0.69</td>
</tr>
<tr>
<td>200</td>
<td>0.50</td>
</tr>
</tbody>
</table>

The results for the different grammages tested are summarized in Table 4.2. With low grammage (20 g/m² and 60 g/m²), the energy supplied was somewhat higher than what theoretically needed for evaporative drying. It is conceivable that the excess energy could be due to the heat-up of the felt and of the water contained therein.

When samples with higher grammages were used, the slopes decreased to values lower than 1 for 120 g/m² and 200 g/m² samples. For the latter samples, the energy supplied was therefore lower than what is necessary for evaporation. It should be noticed that the trend lines plotted in Figure 4.2 have been forced to
cut the vertical axis at the origin. Yet, this simplification implied no significant loss of predictive capacity\(^1\).

Unfortunately, the data in Figure 4.2 were affected by serious experimental uncertainties in spite of the fact that they are based on some 200 individual pressing experiments. This is due to at least three concurrent causes: (i) some variation in basis weight and initial dryness could be observed between samples within a single series, since the paper samples were cut out of individually formed hand-sheets; (ii) the repeatability of the pressing impulse applied by the electrohydraulic press is reduced with pulses of short duration and (iii) the experimental uncertainty in the determination of both the Supplied Energy and the Theoretical Heat of Evaporation is significant. In conclusion, we believe that a significantly more well-behaved set of data could be obtained by performing a much larger number of carefully controlled pressing experiments, resulting in a better statistical significance.

### 4.2 Study of the Internal Sheet Temperature Profile

The four plots of Figure 4.2 provide a somewhat weak indication that the energy efficiency of impulse pressing can be grammage dependent, with an energetically favorable “impulse effect” appearing only at higher grammages. Yet, the results of Figure 4.2 do not allow to discriminate among the different phenomena proposed in the literature and previously analyzed in the Introduction.

For this purpose, we measured the internal temperature profile for paper samples of different grammages, obtained by couching together an appropriate number of 20 g/m\(^2\) and 60 g/m\(^2\) sheets and embedding thermocouples at different elevations. Figure 4.3 reports the typical result of a sheet temperature profile experiment in which the points of first and last contact and maximum applied load are marked with broken vertical lines. Here a 300 g/m\(^2\) SBK sample was pressed under a 28 ms extended press pulse. Not dissimilarly from Lucisano (2000), we found that with appropriate temperature and pressure pulses, the internal temperature signal presented an evident peak appearing as soon as the applied pressure was released.

\(^1\)The \(R^2\) values of trend lines with two free parameters were less than 1 percent higher than the ones reported here, for all grammages tested.
Figure 4.3: Temperature profile in a sheet with grammage 300 g/m². The sheet was pressed with a 28 ms extended press pulse. The plot reports the temperature of the hot plate and of the five thermocouples embedded in the sample at a distance of 20, 40, 60, 80 and 240 g/m² below the hot surface of the sheet. Lines (A), (B) and (C) mark respectively the contact point, the point of maximum applied load and the last point of contact between the sheet and the hot plate.

When we studied the internal sheet temperature history for pulses of the same shape and length of those serving as the basis for the data of Figure 4.2, we observed a clear dependence on basis weight. No peaks in the internal temperatures could be seen when working with samples with grammage lower than 120 g/m². Yet peaks analogous to those illustrated in Figure 4.3 could be seen for samples of 120, 200 and 300 g/m². Moreover, Lucisano (2000) found the same behavior for SBK sheets with grammage of 500 g/m², although the experiments were performed with somewhat longer press pulses there.

We interpret our data as an indication of a flashing phenomenon inducing water displacement in the thickness direction of the sheet. Since the mechanism proposed by Lucisano (2000) is very similar to that originally suggested for impulse technology by Wahren (1978), we propose that it could be termed “flashing assisted displacement dewatering”.

On the basis of our experimental results, we suggest that the energy efficiency of impulse technology presents a grammage dependent behavior. At low grammages, the phenomenon has no energetic advantage over the combination of traditional wet pressing accompanied by evaporative drying. As the gram-
mage increases, a weak improvement in the energy efficiency was observed; this implies that the energy supplied was lower than what is needed for evaporative drying. Yet, none of our pressing experiments presented any indication of a steam assisted displacement dewatering acting in the first part of the nip. Unfortunately, our experiments give us no means of assessing the role of temperature related effects on liquid dewatering. Still, we propose that the slightly improved energy efficiency we observed at higher grammages can be correlated with the flashing assisted water displacement that could be observed there.

The dependency of the dewatering efficiency on grammage can be connected to Terzaghi’s description of the mechanics of compressible porous media saturated with fluids (Terzaghi, 1944): in such a system, the externally applied pressure is counterbalanced by the additive sum of the stress in the solid matrix and of the hydraulic pressure of the fluid. This idea was applied to the compression behavior of paper webs by Campbell (1947). As a result, the operations of press nips are traditionally divided in two categories: (i) In the first case, the press nip is thought to be compression controlled. Here, the mechanical stress in the fiber network is the dominating factor and the maximum web dryness is determined by the applied pressure, with no effect of the pressing time and/or any creep effects. On the other hand, (ii) the nip can be considered flow controlled when the viscous resistance between the water and fibers controls the amount of dewatering. Here, web dryness increases with the residence time of the nip. As a consequence of the applicability of Terzaghi’s principle to flow-limited nips, the web layers closer to the felt are compacted first, with the maximum density at the sheet-felt interface. MacGregor (1983, 1989) described this phenomenon as stratification and its existence has been observed in laboratory experiments (Burns et al., 1990, 1993). Moreover, the resulting density profile in the thickness direction of the sheet has been measured in dry paper (Szikla & Paulapuro, 1989; Szikla, 1992).

In our impulse pressing experiments, we can assume that liquid dewatering tends to be flow controlled at high grammages. Then, the viscous resistance between the water and fibres controls the amount of drainage in the liquid phase. As a consequence, water in the vicinity of the hot pressing surface can be kept at high pressures in the nip, if the the grammage is sufficiently high. The water is therefore forced to remain in the liquid phase, despite the fact that its temperature is much higher than the boiling point at atmospheric pressure. If this situation occurs, phase transition from liquid water to steam occurs instantaneously when the pressure is released, since the top layer water within the sheet is around 200°C (Figure 4.3). This phenomenon, with explosive character, is
known as “flashing” and it is generally accepted as the cause of delamination. Indeed, our experiments show that delamination appears simultaneously with what we identified as a displacement mechanism.

4.3 Multiple Press Pulses

If impulse technology has to accept delamination to achieve a displacement effect and thus save energy, the technical solution patented by Vomhoff (2000) could be of high value. Vomhoff suggests that delamination can be completely avoided by finely tuning the pressing profile by means of multiple pulses. Additionally, it is claimed that, if delamination occurs, the web might be compressed again, totally or to a certain extent, and thus the delaminated area can be at least partly cured and repaired. Indeed, this idea is very interesting, if it proves to be working; yet, the author is not aware of any published study investigating this proposed solution.

Here, a study has been done, where a series of two to five identical press pulses was tested (Figure 4.4). Five microthermocouples were embedded at different levels into SBK sheets with grammage of 240 g/m². The sheets were pressed in position controlled mode due to the fact that the MTS equipment could not press multiple pulses in load control mode. The pulse were of extended type. The results can be observed in Figure 4.4. The interesting aspect of these two plots is that a temperature peak can be seen even when the fifth press pulse is unloaded. Whether the flashing affect is strong enough in the second to fifth pulse to delaminate the web has not been investigated, but the paper sample is however exposed to an internal expanding force.

4.4 Additional Investigations

In a recent work, Lucisano (2000) utilized a series of laboratory pressing experiments to study the mechanism of heat transfer with phase change during impulse pressing of paper. Unfortunately, that work was based on extremely simplified model experiments, and their validity should be tested in conditions closer to the industrially relevant processes. We repeated the aforementioned study and widened its scope by performing a series of approximately 100 experiments to address the issues raised in the Introduction. Space limits hinder
us from reporting the results of all of the tests we performed. Yet the main conclusions can be summarized in the following points:

(i) The use of a rigid porous plate of sintered glass as opposed to a pressing felt as a backing material had no qualitative influence in the results. Peaks in internal temperature upon unloading of the nip were observed using pressing felts as evidenced in Figure 4.3 and Figure 4.4.

(ii) The control mode of the MTS platen press had no qualitative effects on the overall behavior as peaks in the internal temperatures of the sheet could be observed unloading the press both in position control mode and in load control mode.

(iii) Three types of press pulses were investigated in this study: a Haversine pulse, a triangular pulse and an extended press pulse. We found no or very little evidence of the existence of temperature peaks upon unloading a Haversine pulse. Yet, flashing assisted displacement dewatering is present in connection with both triangular pulses (Lucisano, 2000) and extended press pulses (Figure 4.3).
The shortest press pulse used by Lucisano (2000) had a duration of approximately 120 ms, which is unreasonably long when compared with most industrial applications. We tested pulses with dwell times as short as 15 ms and could observe the same qualitative behavior as Lucisano. Figure 4.3 provides an example of a 28 ms long pulse.

The only open issue we could not address is the influence of the load geometry of a platen press as opposed to a shoe and roll press. A large majority of the basic research works published in the literature is performed on platen presses, since they are easier to study, to connect to accurate instrumentation devices and to control. A noteworthy exception is the work recently performed on a laboratory scale shoe-press at the Division of Paper Technology of the Royal Institute of Technology, KTH (Nilsson & Norman, 2000; Nilsson, 2001). Yet, in consideration of the aforementioned practical aspects, the trials we performed in this thesis were made on a platen press.
Chapter 5

Summary

This thesis presents the main results of a laboratory investigation of the mode of dewatering of wet paper webs during an impulse pressing event. We tried to study this issue by two independent sets of experiments performed on a laboratory press simulator.

We found indications that a displacement dewatering mechanism can assist wet pressing and evaporative drying in accounting for the high dewatering rates observed during impulse pressing of paper. Yet, this mechanism seems to be grammage dependent and we found that a minimum basis weight of approximately 120 g/m$^2$ is required for its existence.

We propose that this kind of “impulse effect” should be interpreted as an example of the “flashing-assisted displacement dewatering” originally proposed by Lucisano (2000).

Additionally we tested a patented solution to prevent or repair delamination in connection to impulse pressing of wet paper. It is proposed that the use of multiple press pulses with carefully controlled profile should be effective in this respect. The results of our measurements clearly show that paper samples experienced internal flashing even after five consecutive pulses. Yet, it should be pointed out that we did not measure the mechanical properties of sheets treated with multiple pulses and that additional work is required in this respect.
Acknowledgements

It is always with somebody’s help and encouragement that a Master Thesis is feasible. Therefore, I would like to express my sincere gratitude to:

- My tutor Lic. Eng. Marco “The Martyr” Lucisano, STFI, whom I cannot find words for expressing my gratitude to, but without his help this thesis would never have been written. I especially thank him for always having the time for more or less stupid questions or discussions concerning everything between heaven and hell. I thank him for his support, for being a pain in the ass but most for being a very wonderful friend.

- My tutor Lic. Eng. Peter Sedin (LuleåTechnical University), whom kindly gave me the second chance to finish this thesis.

- Sune Karlsson, STFI, for patience and good comments and help with the platen press experiments with the MTS equipment.

- Daniel Söderberg, STFI, for bringing thesis student that I can tease with. For his support and education in salary negotiation.

- Patrick Myhrman for staying longer at STFI than necessarily. For disturbing me with the worst jokes ever been told. For accompanying me at the late evenings at STFI.
**Notation**

\( c_p \) Specific heat capacity \( J/m^3 \cdot K \)

\( h_{ev} \) Latent heat of evaporation \( J/kg \)

\( h_l \) Enthalpy of liquid water \( J/kg \)

\( k \) Thermal conductivity \( W/m \cdot K \)

\( MR \) Moisture ratio \( kg/kg \)

\( q \) Heat flux \( W/m^2 \)

\( Q \) Evaporation energy per unit sample area \( J/m^2 \)

RH Relative humidity

SBK Softwood bleached kraft

SR Schopper-Riegler

\( t \) Time \( s \)

\( T_s \) Surface temperature \( ^\circ C \)

\( w \) Basis weight \( kg/m^2 \)

**Greek Symbols**

\( \alpha \) Thermal diffusivity \( m^2/s \)

\( \rho \) Density \( kg/m^3 \)

\( \Theta \) Dummy temperature variable \( ^\circ C \)

**Subscripts**

\( 0 \) First contact point

\( 1 \) Last contact point

\( ev \) Evaporation

\( l \) Liquid phase

\( s \) surface

\( wet \) wet pressing
Bibliography


VAN TILBURG, J. 1975 Expanding fibrous or plastic material by adding puffing agent under pressure and subsequent pressure release. USA Patent no. 3,880,705.


Wahren, D. 1982 Method and apparatus for the rapid consolidation of moist porous web. USA Patent no. 4,324,613.

function f = taler(TTemperature,TTime,k,rho,cp)

%**************************************************************************
%* T A L E R
%**************************************************************************
%* taler(TTemperature,TTime,k,rho,cp) calculates the heat flow into
%* an infinite half space of a solid with:
%* - thermal conductivity: k [W/m,K]
%* - density: rho [kg/m^3]
%* - specific heat capacity: cp [J/kg,K]
%* The theory and the equations are described in:
%* 3733-3748.
%* This m-file comprises two parts:
%* (i) Smoothening of the experimental data with the digital filter of Equation (19) in Taler.
%* (ii) Calculation of the heat flow using Equations (11), (12) and (13) in Taler.
%* OBS! In order for the digital filter to treat each data point in the same manner, the scanning of data should start at least 5 time steps Deltat before the cooling or heating process starts.

if ~isequal(size(TTime),size(TTemperature))
    error('The time and temperature vectors are not of the same size!')
end
% DIGITAL FILTER

disp(' Smoothening experimental data! Please wait!')

Flow = zeros(size(TTemperature));
y = zeros(size(TTemperature));
dy = zeros(size(TTemperature));
ddy = zeros(size(TTemperature));
dddy = zeros(size(TTemperature));
Deltat = TTime(2)-TTime(1);

for i = 6:(length(TTemperature)-5)
    y(i) = 1/429*(-36*TTemperature(i-5)+9*TTemperature(i-4)+44*TTemperature(i-3)+69*TTemperature(i-2)+84*TTemperature(i-1)+89*TTemperature(i)+84*TTemperature(i+1)+69*TTemperature(i+2)+44*TTemperature(i+3)+9*TTemperature(i+4)-36*TTemperature(i+5));
    dy(i) = 1/(5148*Deltat)*(300*TTemperature(i-5)-294*TTemperature(i-4)-532*TTemperature(i-3)-503*TTemperature(i-2)-296*TTemperature(i-1)+296*TTemperature(i+1)+503*TTemperature(i+2)+532*TTemperature(i+3)+294*TTemperature(i+4)-300*TTemperature(i+5));
    ddy(i) = 5/143/Deltat^2*(TTemperature(i-5)+2/5*TTemperature(i-4)-1/15*TTemperature(i-3)-2/5*TTemperature(i-2)-3/5*TTemperature(i-1)-2/3*TTemperature(i)+3/5*TTemperature(i+1)+2/5*TTemperature(i+2)-1/15*TTemperature(i+3)+2/5*TTemperature(i+4)+TTemperature(i+5));
    dddy(i) = 5/143/Deltat^3*(-TTemperature(i-5)+1/5*TTemperature(i-4)+11/15*TTemperature(i-3)+23/30*TTemperature(i-2)+7/15*TTemperature(i-1)-7/15*TTemperature(i+1)-23/30*TTemperature(i+2)-11/15*TTemperature(i+3)-1/5*TTemperature(i+4)+TTemperature(i+5));
end

disp(' Data smoothening perfomed.')
\begin{verbatim}
\%--------------------------------------------------------------------
\% HEAT FLOW CALCULATION
\%--------------------------------------------------------------------

disp(' Solving for the heat flow. ')

for M = 10:(length(TTemperature)-9)
    FlowNow = 0;
    disp(num2str(M))
    for i = 1:(M-1)
        Pi = TTime(M+1)-TTime(i);
        Ri = TTime(M+1)-TTime(i+1);
        Fi = y(i)+dy(i)*Pi+ddy(i)/2*Pi^2+dddy(i)/6*Pi^3;
        Vi = dy(i)+ddy(i)*Pi+dddy(i)/2*Pi^2;
        Wi = ddy(i)+dddy(i)*Pi;
        FlowNow = FlowNow+(Vi*(Pi^(1/2)-Ri^(1/2))-Wi/3*(Pi^(3/2)-...Ri^(3/2))+dddy(i)/10*(Pi^(5/2)-Ri^(5/2)));
    end
    PM = TTime(M+1)-TTime(M);
    VM = dy(M)+ddy(M)*PM+dddy(M)/2*PM^2;
    WM = ddy(M)+dddy(M)/2*PM;
    FlowNow = FlowNow+(VM*PM^(1/2)-WM/3*PM^(3/2)+dddy(M)/10*PM^(5/2));
    FlowNow = FlowNow*2*sqrt(k*rho*cp/pi);
    Flow(M+1) = FlowNow;
end

f = Flow;
\end{verbatim}
%********************************************************************
%* H E A T F L O W *
%********************************************************************
%* Heat Flow provides tools to calculate the heat flow out of *
%* an infinite half space of a solid with: *
%* - thermal conductivity: \( k \) [W/m,K] *
%* - density: \( \rho \) [kg/m^3] *
%* - specific heat capacity: \( c_p \) [J/kg,K] *
%* This file is written for the analysis of hot pressing model *
%* experiments on a MTS platen press. *
%* Moreover, tools for the identification of the first and last *
%* point of contact between the sheet and the hot press and for the *
%* calculation of the total heat transferred per unit area. *
%* A .out file is produced to save the instantaneous heat flux *
%* values. *
%* The theory and the equations are described in: *
%* Taler, Jan (1996) "Theory of Transient Experimental Techniques *
%* for Surface Heat Transfer"; Int. J. Heat Mass Transfer, 39(17): *
%* 3733-3748. *
%* *
%* OBS! In order for the digital filter to treat each data point in *
%* the same manner, the scanning of data should start at least *
%* 5 time steps Deltat before the cooling or heating process *
%* starts. *
%********************************************************************
%* STFI, 20000803/20010327, ML *
%********************************************************************

clear
c1c
disp([' This file will calculate the heat flux from the hot',...
' plate during a MTS '])
disp(' platen press experiment. ')
disp('')
fid = 0;
while fid < 1
    FileName = input([' Type the complete path and name of the',...
' data file you want to open: '], 's');
    [fid, message] = fopen(FileName);
    if fid == -1
        disp(message)
end
end

Heading = fgets(fid);
DefaultCol = 4;
DefaultTemp = 2;             % Change here
DefaultSave = [2,3,4];       % and here if necessary.
disp(' The column titles saved on file are:')
disp(' ')
disp(Heading)
disp(' ')
disp([' By default I will assume that column ',...
     num2str(DefaultTemp),' contains the temperature of the hot '])
disp([' plate and save columns ', num2str(DefaultSave),...
     ' in the output file.'])
disp(' ')
YesNo = 'reset';
while ismember(YesNo, ['Y','y','N','n']) == 0
    home
    YesNo = input(' Do you want to continue (Y/N): ','s');
end
if ismember(YesNo, ['N','n'])
    Temp = str2num(input(' Enter temperature column number: ','s'));
    SaveVector = ...
        str2num(input(' Enter vector with columns to save: ','s'));
    Columns = ...
        str2num(input(' Enter number of columns on file: ','s'));
else
    Temp = DefaultTemp;
    SaveVector = DefaultSave;
    Columns = DefaultCol;
end

SaveFormat = '
';
for k = 1:Columns
    SaveFormat = [SaveFormat,'%f '];
end
SaveFormat = SaveFormat(1:(length(SaveFormat)-2));
SaveFormat = [SaveFormat, '\n'];
Data = fscanf(fid,SaveFormat,[Columns,inf]);
Data = Data';
Status = fclose(fid);
Sampling = 0.001;  % This can be improved
Data(:,1) = [0:Sampling:(Sampling*(size(Data,1)-1))];

disp('  ')
disp(' Data file imported!')
disp('  ')

%--------------------------------------------------------------------
% Data plotting
%--------------------------------------------------------------------

disp(' Plotting data in Figure 1')
figure(1)
clear
subplot(3,1,1)
plot(Data(:,1),Data(:,Temp))
ylabel('Hot Plate Temperature [C]')
subplot(3,1,2)
plot(Data(:,1),Data(:,(Temp+1)))
ylabel('Load [mv]')
subplot(3,1,3)
plot(Data(:,1),Data(:,(Temp+2)))
ylabel('Position [mV]')
xlabel('Time [s]')

YesNo = 'reset';
while ismember(YesNo, ['N','n']) == 0
    while ismember(YesNo, ['Y','y','N','n']) == 0
        home
        YesNo = ...
        input(' Do you want to zoom in on the x-axis? (Y/N): ','s');
    end
    if ismember(YesNo, ['Y','y'])
        xmin = str2num(input(' Enter xmin: ','s'))/Sampling+1;
        xmax = str2num(input(' Enter xmax: ','s'))/Sampling+1;
        nints = str2num(input(' Enter no. intervals: ','s'));
        figure(1)
clear
        subplot(3,1,1)
        plot(Data(xmin:xmax,1),Data(xmin:xmax,Temp))
        set(gca,'XTick',([xmin:(xmax-xmin)/nints:xmax]-1)*Sampling)
ylabel('Hot Plate Temperature [C]')
subplot(3,1,2)
plot(Data(xmin:xmax,1),Data(xmin:xmax,(Temp+1)))
set(gca,'XTick',([xmin:(xmax-xmin)/nints:xmax]-1)*Sampling)
ylabel('Load [mv]')
subplot(3,1,3)
plot(Data(xmin:xmax,1),Data(xmin:xmax,(Temp+2)))
set(gca,'XTick',([xmin:(xmax-xmin)/nints:xmax]-1)*Sampling)
ylabel('Position [mV]')
xlabel('Time [s]')
YesNo = 'reset';
else
  xmin = 1;
xmax = size(Data,1);
nints = 10;
end
end

%--------------------------------------------------------------------
% Data Smoothening
%--------------------------------------------------------------------

YesNo = 'reset';
while ismember(YesNo, ['N','n']) == 0
  while ismember(YesNo, ['Y','y','N','n']) == 0
    home
    YesNo = ... 
    input([' Do you want to smoothen the temperature signal?',...
           ', (Y/N): '],',s');
  end
if ismember(YesNo, ['Y','y'])
  keyboard
end
figure(1)
clf
subplot(3,1,1)
plot(Data(xmin:xmax,1),Data(xmin:xmax,Temp))
set(gca,'XTick',([xmin:(xmax-xmin)/nints:xmax]-1)*Sampling)
ylabel('Hot Plate Temperature [C]')
subplot(3,1,2)
plot(Data(xmin:xmax,1),Data(xmin:xmax,(Temp+1)))
set(gca,'XTick',([xmin:(xmax-xmin)/nints:xmax]-1)*Sampling)
ylabel('Load [mv]')
subplot(3,1,3)
plot(Data(xmin:xmax,1),Data(xmin:xmax,(Temp+2)))
set(gca,'XTick',([xmin:(xmax-xmin)/nints:xmax]-1)*Sampling)
ylabel('Position [mV]')
xlabel('Time [s]')
YesNo = 'reset';
end
end

%--------------------------------------------------------------------
First and Last Contact Points
%--------------------------------------------------------------------

disp(' ')
[MaxLoad,J] = min(Data(:,Temp+1));

ExcessPoints = 10;
[StartLoad,StartPoint] = max(Data(J-20:J,Temp+1));
[EndLoad,EndPoint] = max(Data(J:J+20,Temp+1));
StartPoint = StartPoint+J-20-ExcessPoints;
EndPoint = EndPoint+J+ExcessPoints;

YesNo = 'reset';
while ismember(YesNo, ['Y','y']) == 0
    figure(1)
    clf
    subplot(3,1,1)
    plot(Data(StartPoint:EndPoint,1),Data(StartPoint:EndPoint,Temp))
ylabel('Hot Plate Temperature [C]')
    subplot(3,1,2)
    plot(Data(StartPoint:EndPoint,1),Data(StartPoint:EndPoint,...
         (Temp+1)))
ylabel('Load [mv]')
    subplot(3,1,3)
    plot(Data(StartPoint:EndPoint,1),Data(StartPoint:EndPoint,...
         (Temp+2)))
ylabel('Position [mV]')
xlabel('Time [s]')
    YesNo = 'reset';
    while ismember(YesNo, ['Y','y','N','n']) == 0
disp([' I am integrating on the interval shown in Figure (1) '])

YesNo = input(' Do you want to continue? (Y/N): ','s');
end
if ismember(YesNo, ['N','n'])
    NewStartPoint = ...
    input([' Enter the first point of integration (',...    
           num2str(StartPoint),'): '],'s');
    if ~isempty(str2num(NewStartPoint))
        StartPoint = str2num(NewStartPoint);
    end
    NewEndPoint = ...
    input([' Enter the last point of integration (',...    
           num2str(EndPoint),'): '],'s');
    if ~isempty(str2num(NewEndPoint))
        EndPoint = str2num(NewEndPoint);
    end
end

k=60; %[W/m,K] % This can be improved
rho=7800; %[kg/m3]
cp=480; %[J/kg,K]

HeatFlux = taler(Data(StartPoint:EndPoint,Temp),...    
                  Data(StartPoint:EndPoint,1),k,rho,cp);

SaveData = [Data(StartPoint:EndPoint,:),HeatFlux];

disp(' ')
disp(' Plotting the heat flux in Figure 2')
disp(' ')
figure(2)
plot(SaveData(:,1),SaveData(:,size(SaveData,2)))
xlabel('Time [s]')
ylabel('Heat Flux ')
OUTPUT on file

% Change the following lines for generality
SaveName = [FileName(1:(length(FileName)-3)),'out'];
HeadingOut = 'Time Temp Load Pos Flux';
SaveFormat = '%9.7f %9.7f %9.7f %9.7f %9.7f
';

(fid,message) = fopen(SaveName,'a');
if fid == -1
    disp(message)
else
    fprintf(fid,[HeadingOut,'\n']);
    fprintf(fid,SaveFormat,SaveData');
end
fclose('all')

Integration

TotalHeat = Sampling*(sum(SaveData(:,size(SaveData,2)))...
    -1/2*(SaveData(1,size(SaveData,2)))*...
    SaveData(length(SaveData),size(SaveData,2))));

disp(' ')
disp([' The total heat transferred is : ', num2str(TotalHeat)]

disp(' ')
END OF FILE