CHALMERS

The influence of sheet non-uniformity on drying efficiency

Method development using IR-thermography

Master of Science Thesis in the Master's Programme, Innovative and Sustainable Chemical Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2012

MASTER’S THESIS

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Acknowledgements

This report represents the master thesis of Louise Nilsson for achieving her Master's degree in chemical engineering at Chalmers University of Technology. The author of this report would like to thank Professor Hans Theliander for allowing her to perform this thesis at Innventia AB. The continuous support during the course of this project work by Aron Tysén, Caroline Hyll and Hannes Vomhoff was most appreciated.

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Abstract

In this project the effect of sheet non-uniformity on through air drying for tissue paper was investigated. A method for studying the drying process using an infrared (IR) thermo camera was developed and evaluated. Here, an experimental suction box was connected to a centrifugal fan. A wet hand sheet was put onto the suction box and the drying was observed using an IR thermo camera. Experiments were conducted with sheets of four different grammages, between 15 and 47 g/m^2. The images obtained were then interpreted using ThermaCAM^{TM} Researcher Professional and MatLab.

In the initial phase of the drying process, a considerable drop in temperature down to a minimum average temperature was observed. During the drying process, the average temperature increased continuously. The dying process was considered to be completed, when the change in local sheet surface temperature was less than 0.5°C during 10 seconds. In order to analyse the drying non-uniformity, a temperature criterion was introduced, where no measured points in a sheet were considered dry before passing a set temperature.

The results showed that the minimum average temperature for the sheet decreases as grammage increases. They also showed a clear increase in drying time as the grammage increased. The non-uniformity in drying increased with grammage, giving an increase in time span between minimum and maximum drying time from 10 seconds for 15g/m^2 to 25 seconds for 47g/m^2.

Key words: Drying, dewatering, water removal, thermography, infrared thermography, tissue paper, TAD

Table of contents

1 Introduction

The production of paper takes place by dewatering a pulp slurry on a paper machine, which consists of three main sections: forming, pressing and drying section[1, 2]. In the forming and pressing section, the water is removed by ways of mechanical dewatering Due to water being bound to the fibres, there exists a limit to how much water can be removed by pressing [6].

In the drying section, the final step, the remaining water is removed by thermal drying[1]. Although less than 1% of the total water is removed in the drying section, it consumes the largest amount of energy. This since thermal removal is less energy-effective than removing the water by mechanical dewatering as the water has to be evaporated. An increased understanding of the drying process is therefore interesting, and could lead to energy savings.

1.1 Background

1.1.1 Non-uniformity of paper and the process of drying

In paper manufacturing, a fibre suspension is dewatering on a permeable wire, leaving a wet fibre web[1]. The cellulose fibres in suspension have a tendency to form connected networks, flocks. Due to the flocculated state of the fibre suspension, the wet fibre web has a non-uniform mass distribution. This non-uniform mass distribution can be seen as a local variation in grammage.

The drying process for paper can be divided into three phases; the heating phase, constant drying rate phase and falling drying rate phase[2]. Change in temperature and moisture content for a generalized drying process can be seen in figure 1.

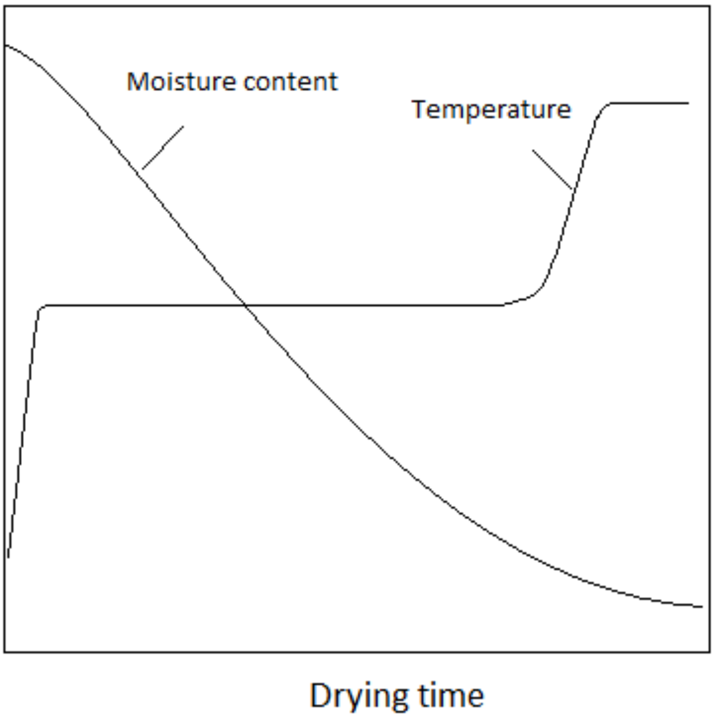


Figure 1. Generalized drying process of a paper web showing moisture content and temperature as a function of time.

During the heating phase, the temperature increases until the sheet reaches equilibrium temperature. In the constant drying rate phase, the temperature becomes constant as all the energy goes to evaporating the moisture[3]. After a time, the resistance for transport of water and vapour will increase, and when the surface is no longer kept wet, the temperature will increase at the same time as the drying rate will decrease[4].

Previous studies of through drying of paper (see section 1.1.3 below) show that for grades with low grammage (tissue), the constant drying rate period may not exist for industrial drying conditions[5].

1.1.2 Tissue

Tissue paper consists of products such as kitchen and toilet paper, with a grammage in the range of 15-50 g/m^2[1]. Important qualities include softness, smoothness and a high ability to absorb water. Smoothness and softness are subjective properties, and relates to the perception of the user. A paper with higher bulk, the inverse of the density, generally has a higher ability to absorb water.

The most common technique for drying of tissue is Yankee drying, in which the sheet is dried on one large Yankee-cylinder with a diameter of 5-7 m. A press roll presses the paper web against the Yankee, which is heated from the inside with steam. By pressing the paper against the cylinder, a dry content of 35-45% is achieved prior to the thermal drying. The cylinder is covered with a hood in which hot air is blown onto the outside of the web, contributing to the drying.

In recent years, the use of a different technique for tissue drying, through air drying (TAD) has increased, mainly in the USA. It is the principle behind this drying technique that will be studied in this project.

1.1.3 Through air drying

In TAD, the wet web is transported from the forming section onto a TAD wire and dried on an open TAD-cylinder[2]. Air is being sucked through the paper moulds the paper by pressing it against the wire, producing a pattern in the z-direction of the paper[6]. The created pattern gives an increased absorbency and bulk for TAD paper. The principle behind TAD can be seen in figure 2.

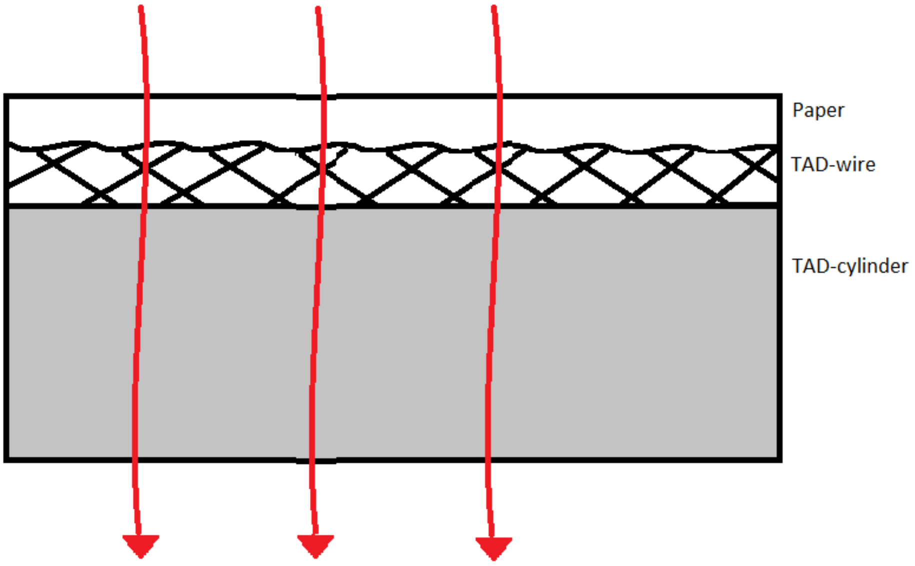


Figure 2. Principle for TAD.

Thermal drying takes place when hot air is sucked through the paper web[2,6]. Air inlet temperature has a maximum temperature of 260°C, and decreases to approximately 120°C when passing through the paper web. After drying, the paper has a dry content of 70-90%. Drying is performed using a constant pressure drop across the sheet, which due to variations in grammage, and thereby permeability, will result in a variation of air flow across a sheet being dried.

Drying takes place through convective heat and mass transfer, as the hot air passes through the web[2]. This gives a very large area for heat transfer, and therefore TAD has very high drying rates. However, the lack of mechanical pressing previous to the drying section gives a dry content of as low as 25% into the drying section. This leads to a very high drying load for TAD, and the use of large amounts of air at high temperature and relatively low velocity gives high energy consumption.

Advantages with TAD are that it gives improved product qualities, the lack of pressing results in a product with higher bulk and water absorbency. Materials savings can be done since less material is needed to achieve a product with the desired qualities.

During TAD, the local variations in air permeability will affect the air flow, resulting in a non-uniform drying[7]. Drying non-uniformity increases during a drying period, and is therefore affected by the initial moisture content. A higher initial moisture content will result in longer drying time and thereby an increase in drying non-uniformity.

It has also been shown that drying non-uniformity is worse for relatively low grammage (~30g/m^2) [8]. As the grammage increases, non-uniformity decreases as the paper becomes thicker and therefore more uniform. For lower grammages, the non-uniformity decreases as the paper behaves increasingly as a screen, and less as a packed bed.

Evaporation of water is an endothermic process[4]. Therefore, a cooling of the paper surface will take place as drying proceeds. This makes it possible to study the process of drying using thermography.

1.1.4 IR Thermography

Thermography is a non-destructive technique, measuring the heat emitted as infrared radiation from the surface of an object, and from this generating an image[9]. The radiation measured is related to temperature through Planck's equation, which gives the temperature for a blackbody. Emissivity is a measure of how much radiation the object emits, compared to a perfect black body of the same temperature.

As paper dries, the emissivity will decrease as the water content decreases. Preliminary measurements performed by Caroline Hyll [10] indicates that for the chemical pulp used in this report, the emissivity is reduced from 0.87 to 0.77 as the dry content increases from 33% to 85%. Setting the emissivity too high should in theory result in the calculated temperature being lower than the actual temperature.

The calculated temperature will also be affected by temperature reflected in the object by the surroundings, atmospheric temperature, humidity and distance between the camera and the object being measured.

1.2 Goal of this thesis

The previously mentioned non-uniformity in material distribution will affect the air flow through the fibre network, and therefore the drying rate. The aim of this master thesis was to understand and quantify the effect of the sheet non-uniformity (formation) on dewatering and drying efficiency. A method for investigating the non-uniformity in TAD using an IR camera was developed and evaluated.

The developed method should enable future studies for investigating the influence of raw material, pulp treatment, sheet structure, grammage and grammage non-uniformity on the dewatering efficiency.

2 Experimental procedure and materials

In the laboratory practice, an experimental suction box was connected to a centrifugal fan. A wet sheet was put onto the wire table and the drying was observed using an IR thermo camera.

2.1 Laboratory sheets

Initially experiments were conducted to produce one sheet with a controlled variation of grammage. The methods used were unsuccessful in producing this type of sheet with sufficient quality and reproducibility with the available equipment. Instead sheets of four different grammages were produced.

Laboratory sheets were made in a sheet former according to Finnish standard, the area of the sheets was 165*165 mm. A bleached chemical softwood pulp (kappa number approximately 0.3) was used to produce sheets with grammage ~15, ~25, ~35 and ~45g/m^2.

The wet sheets were lifted from the wire and placed between two sheets of blotting paper. They were then stored in a refrigerator for approximately 15 h before the experiments were conducted. To determine the initial moisture content of the sheets, five sheets of each grammage was weighted, dried on a hot plate for 20 minutes and then weighted again. The sheets used for analyses were dried on hot plate after filming to determine grammage.

The trials were conducted for all four different grammages, and five sheets were filmed for each grammage.

2.2 Experimental setup

The experimental equipment used in this project consisted of an experimental wire table that was directly connected to a centrifugal fan, as can be seen in the figure 3 below.

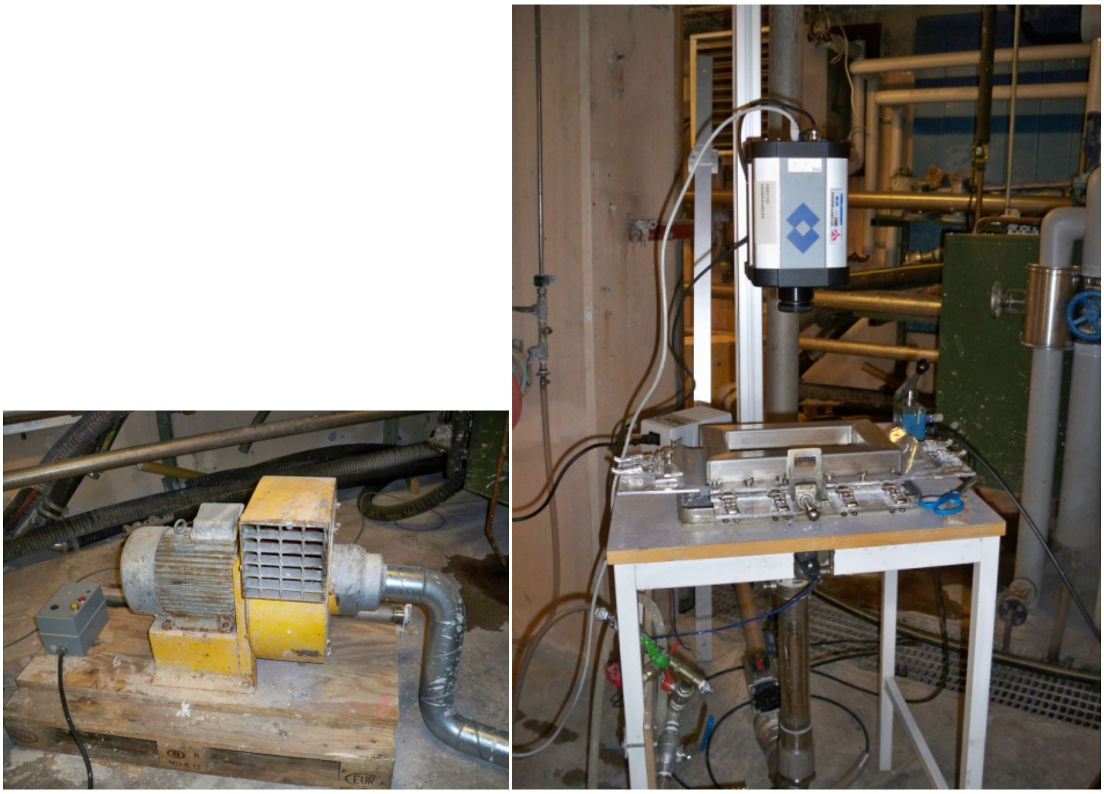


Figure 3. Experimental setup, consisting of a fan connected to a suction box. The camera used for filming was mounted over the suction box.

The suction box was equipped with a pressure valve, making it possible to turn the air on and off instantaneously. When the fan was started, and valve opened, air at room temperature started to flow through the wire. Due to the placement of the equipment, there was no possibility of controlling the temperature of the air passing through the wire, or other factors in the surrounding. Using air at room temperature compared to air of higher temperature, will slow down the drying process and make it possible to study it in more detail.

There existed the possibility of adjusting the air flow to the wire table through a valve, but no possibility to measure the air-flow or pressure drop during trials. Therefore, the air flow was kept at the highest level for all measurements. Since the fan is directly connected to the wire table, an increase in pressure drop will result in a reduced net air-flow.

The wire used was a standard forming wire. A wet laboratory sheet was put onto the wire table, with the excess surrounding wire covered by a plastic film. This was done to prevent a flow of air around the sheet, and have all the drying air pass through the sheet during drying. The sheet was restrained in one direction, holding it in place and preventing shrinkage in this direction.

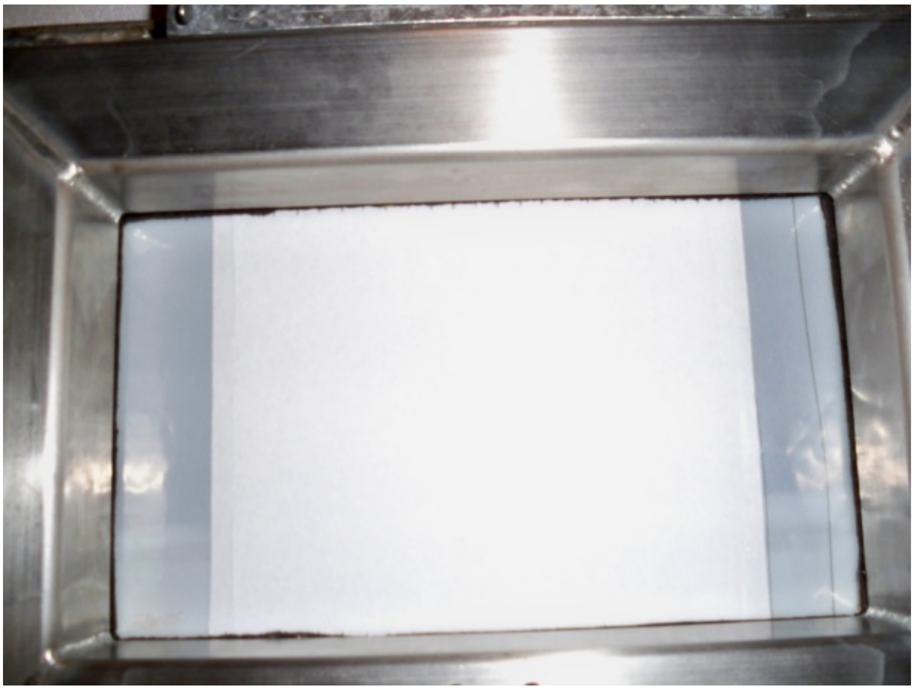


Figure 4. Laboratory sheet placed on wire on suction box. Measurements for area within metal frame 13x22 cm.

A ThermoVision^{TM} SC6000 high-speed infrared camera from FLIR systems was used to measure the temperature of the sheets during drying. Calibration for the temperature interval -10°C-50°C, and a frequency of 30 Hz was set. The measuring accuracy for the camera was ±2°C. More information on the camera can be seen in table 1 below.

Table 1 ThermoVision^{TM} SC6000

Camera	**SC6000 MWIR**
Detector	InSb photodetector
Wavelength sensitivity	3.0-5.0 µm
Full frame size	640 x 512 pixels
Frame rate at full window	126 Hz
Typical field-of-view (FOV)	9.1^0 x 7.2^0

The camera was placed directly above the sample being measured, at a distance of 0.3m. The camera was connected to a computer, using the software ThermaCAM^{TM} - Researcher professional version 2.9 to control the camera, and display the camera image. During recording, the software could not display the image.

When the sheet had been placed on the wire, the recording was started and the pressure valve opened to allow air to flow through the sample. After an initial trial, it was determined that for the sheets with the highest grammage, no detectable change in surface temperature could be seen after approximately 45 seconds. It was decided that each trial should be conducted for approximately 65 seconds. After this time, the recording was stopped and pressure valve closed.

2.2.1 Reflected temperature and atmospheric temperature

To get accurate temperature readings when using the infrared camera, a number of parameters needed to be set. The reflected temperature is a parameter measured to compensate for the radiation reflected in the object. Reflected temperature was measured using a high reflective lambertian gold surface[9]. The measurement was conducted prior to the first trial. The atmospheric temperature for the experiments used in this report was also measured at this point.

2.2.2 Estimated maximum air flow

Since there existed no possibility of measuring the air flow during trials, an experiment was conducted to estimate the maximum air flow produced by the fan. The time for the exhaust of the fan to fill a large plastic bag was measured. This gave an air flow of approximately 40 l/s, recalculating using the area of the exhaust (19x19 cm), and density of air 1.2 kg/m^3 gave a flow of 1.3 kg/m^{2}s.

These measurements were conducted to get a crude approximation of pressure drop and air flow, since these parameters were not measured during trials.

3 Results

Measurements were conducted for finding the grammage and initial moisture content as described in section 2.1 above.

The results from the trials were interpreted using ThermaCAM^{TM} Researcher Professional version 2.9 and MatLab routines written for this project. The MatLab routines can be found in Appendix B.

3.1 Initial moisture content and grammage

3.1.1 Grammage

A mean grammage for the sheets being dried can be seen in table 2 below. Table of all the sheet measurements can be found in table 7, Appendix A.

Table 2 Mean grammage for tested sheets

Mean grammage [g/m2]	Std.Dev
14,86	0,12
25,18	0,35
34,38	0,25
46,95	0,67

When all the sheets had been weighted it was concluded that one of the sheets for the 47 g/m^2 had a very high deviation from the others (a much lower grammage). Since this will affect the results, it was decided to exclude this sheet from the analysis. This lowered the standard deviation for these sheets from 1.68 to 0.67. Because of this, results below only include four measured sheets for the highest grammage.

3.1.2 Initial moisture content

Five sheets of each grammage were weighted to determine initial moisture content. This showed a low variation in initial moisture content for sheets of the same grammage. Therefore, the results were used to determine the moisture content of the actual sheets being dried. This was done by taking the calculated percentage of moisture content and applying it to the sheets that had been tried during the trials.

Table 3 Average initial moisture content

Grammage [g/m2]	Dry content [%]	Moisture content [g]
~15	35,5	0,74
~25	34,2	1,32
~34	33,4	1,87
~47	32,9	2,61

Even though the dry content between grammages differs by less than 3%, the actual amount of moisture being removed increases with grammage. All results can be found in table 8, Appendix A.

3.2 Drying in ThermoCAM^{TM}

To get accurate results for recordings, a number of parameters previously mentioned needed to be set. Set values used to obtain the results included in this report can be seen in table 4.

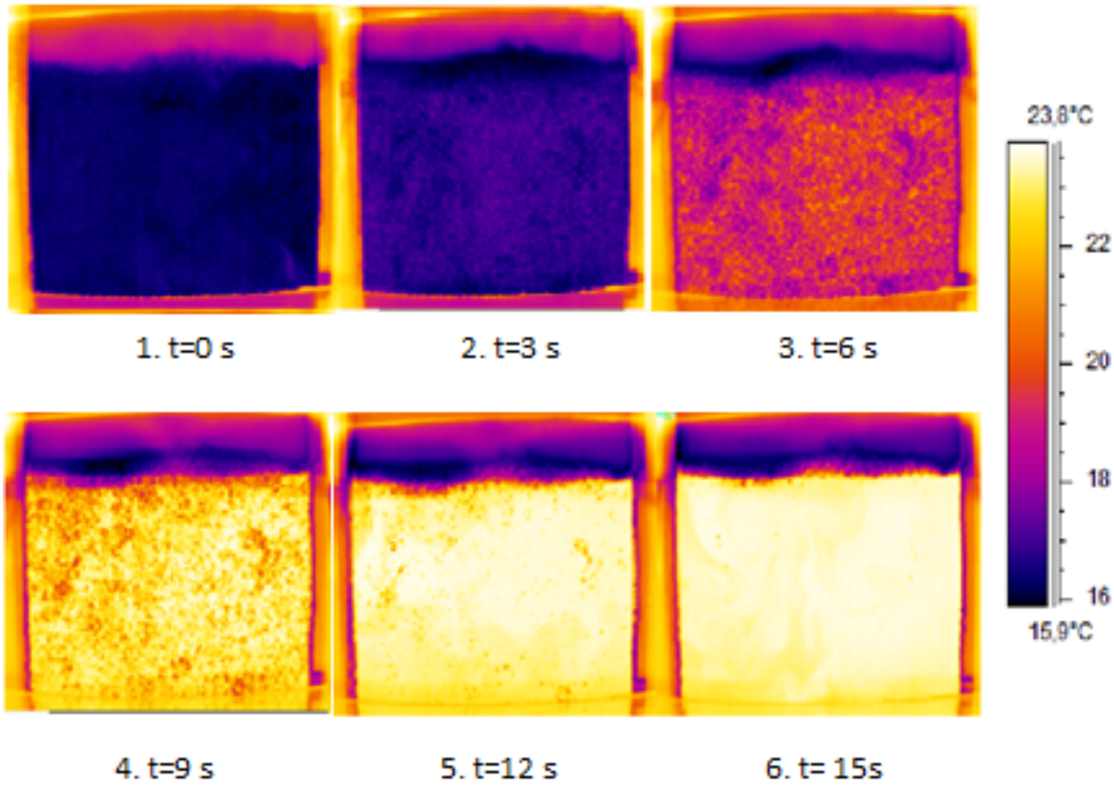
Table 4 Set values in ThermaCAM^{TM} Researcher

Emissivity	0.85*
Distance (camera-recorded object)	0.3 m
Reflected temperature	25.2°C
Atmospheric temperature	23.6°C
Relative humidity	50%**

**Emissivity was set to a constant value*
*** No measurements were made for this parameter, kept at default value*

Although emissivity will change during drying, it was here set to a constant value for the whole sequence.

When studying the images from the recordings in ThemoCAM^{TM}, a clear change in temperature for the surface over time can be seen, which can be seen in figure 5.



1. t=0 s 2. t=3 s 3. t=6 s

4. t=9 s 5. t=12 s 6. t= 15s

Figure 5. Images during drying for grammage for one sheet, ~25 g/m^2.

The temperature of the sheet surface continues to increase until it stabilizes at a value close to the surrounding temperature. The area at the top of the pictures, remaining at a low temperature throughout the recording was due to the wire beneath it being blocked, preventing air flow.

Before further analysis in MatLab, a specific area was selected for analysis, to exclude the area without air flow. Also the effects around the edges were not of interest in this study, and therefore excluded. Selected area is shown in figure 6.

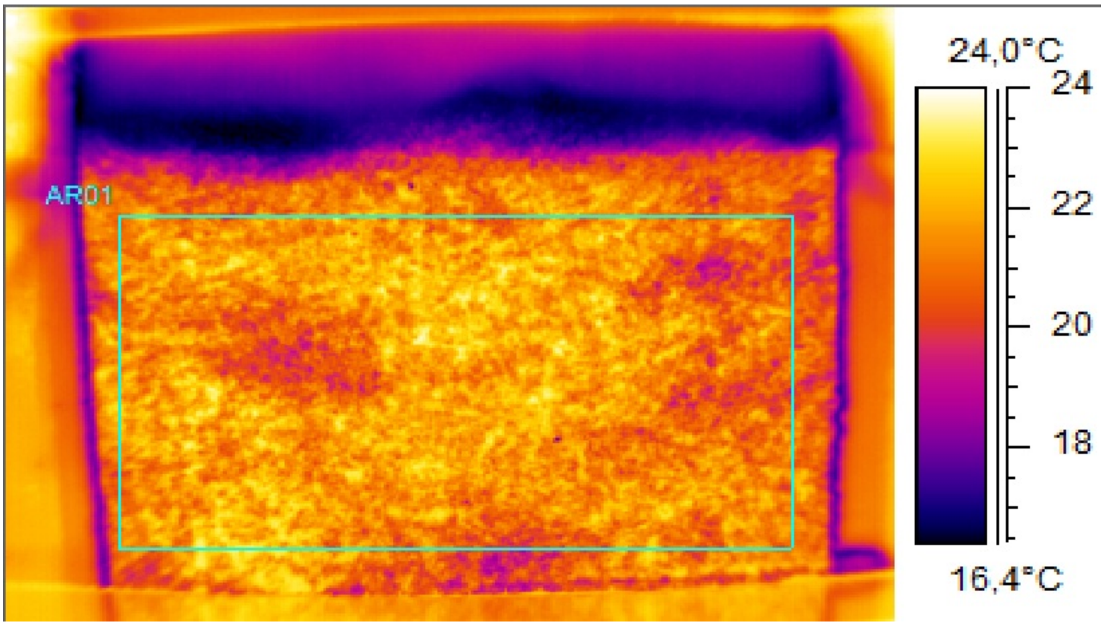


Figure 6. Area selected for further analysis in MatLab.

The selected surface had an area of approximately 7.5x15.5 cm^2, and consisted of a [280,486] matrix containing the measured results (one element in the matrix=one pixel).

3.3 Average temperature over time

To quantify the results obtained in ThermoCAM^{TM}, further analysis was performed using MatLab. The MatLab routines constructed for this can be found in Appendix B.

When converting from ThermoCAM^{TM} to MatLab, the files were first reduced to approximately 10 Hz, giving one measurement every 0.1s. This was done due to restrictions in computer power, making in necessary to reduce the amount of data to increase speed of calculations.

Introducing the air flow gives a sharp decline in sheet temperature. The starting time of the trials was therefore set as when the derivative was below or equal to -1.

Calculating the mean temperature for the selected area, and then taking the mean for all measurements for the same grammage and plotting it against time, gave the result depicted in figure 7 below.

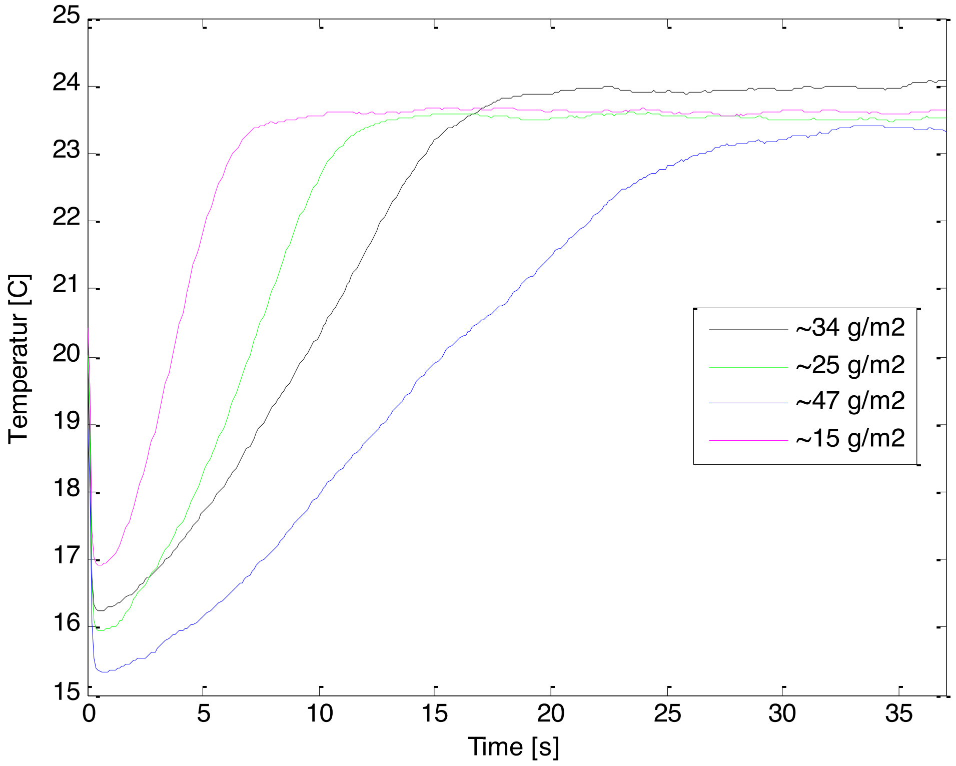


Figure 7. Mean temperature values for all trials within same grammage depicted against time.

When air flow is started, the temperature quickly decreases until reaching a minimum value. Thereafter, the temperature of the sheet starts to increase until it stabilizes at a temperature that appears to be close to the measured atmospheric temperature. This trend could also be seen in ThermoCAM^{TM}.

Stabilisation of temperature takes place at approximately the same temperature for all grammages except 34 g/m^2, which appears to stabilise at a temperature approximately 0.5°C higher. No apparent reason for this could be found, but since these were the last trials conducted, it is possible that some factor in the surroundings had changed (for example, an increase in reflected temperature by 1°C results in a decreased temperature of 0.2°C).

It appears when studying figure 8 that the minimum temperature decreases with an increase in grammage. To study this, the minimum temperature and the temperature when a sheet is considered dry for the different grammages was calculated, and can be seen in table 5. These results showed that the difference between the two temperatures increased with a higher grammage.

Table 5 Difference between minimum temperatures reached and temperature when sheet is considered dry

Grammage g/m2	Tmin [°C]	Tdry* [°C]	delta T [°C]
15	16,9	23,6	6,7
25	16	23,5	7,5
34	16,2	23,9	7,7
47	15,3	23,4	8,1

**For definition of when sheet is to be considered dry, see section 3.4 below*

For results for the individual trials, see Appendix A, table 9. This also shows a variation between the individual trials for sheets of the same grammage.

It is also noted that no period in which the temperature remains at a constant value can be seen for the grammages studied. The rate of temperature change also decreases with increased grammage.

To investigate how much the temperature varies for trials with sheets of the same grammage, the mean temperature for all trials were plotted in figure 8.

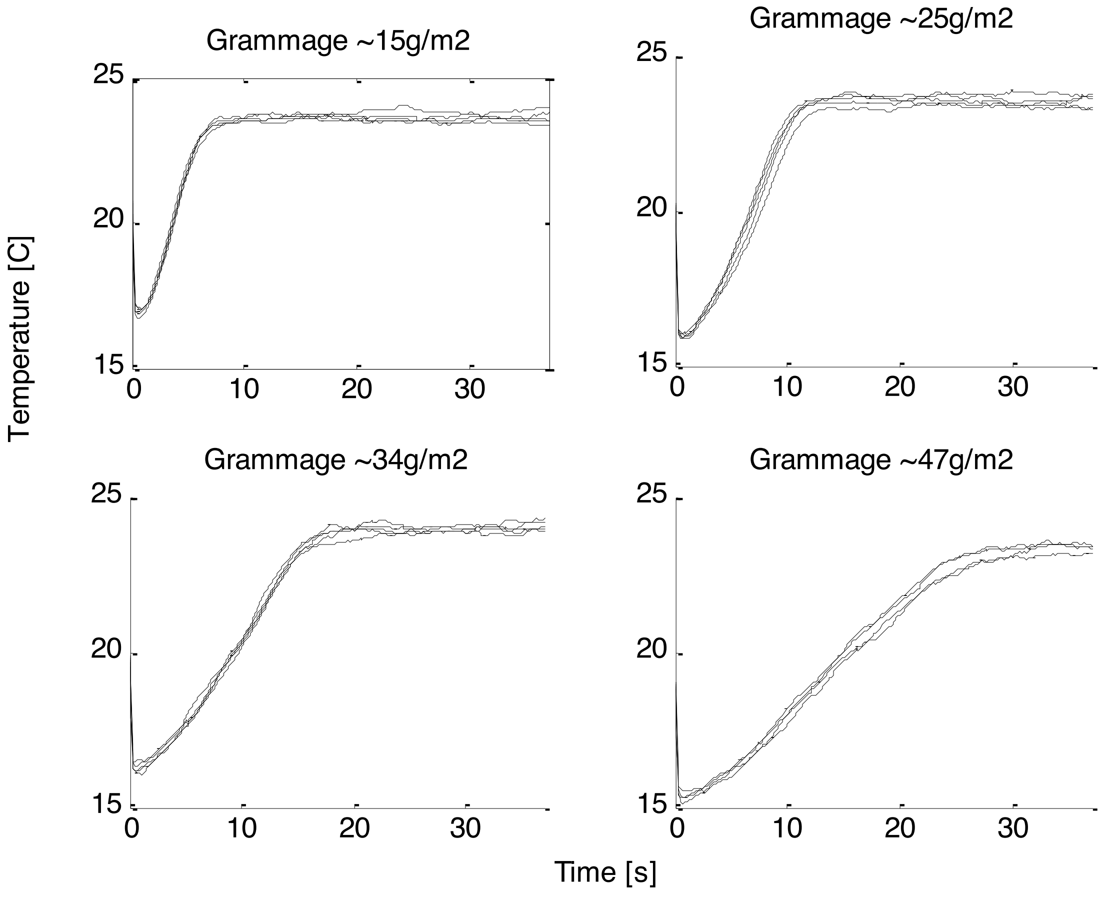


Figure 8. Mean temperature for all trials plotted against time.

When studying the individual trials (figure 9), an effect that was cancelled out when looking at the averages could be detected.

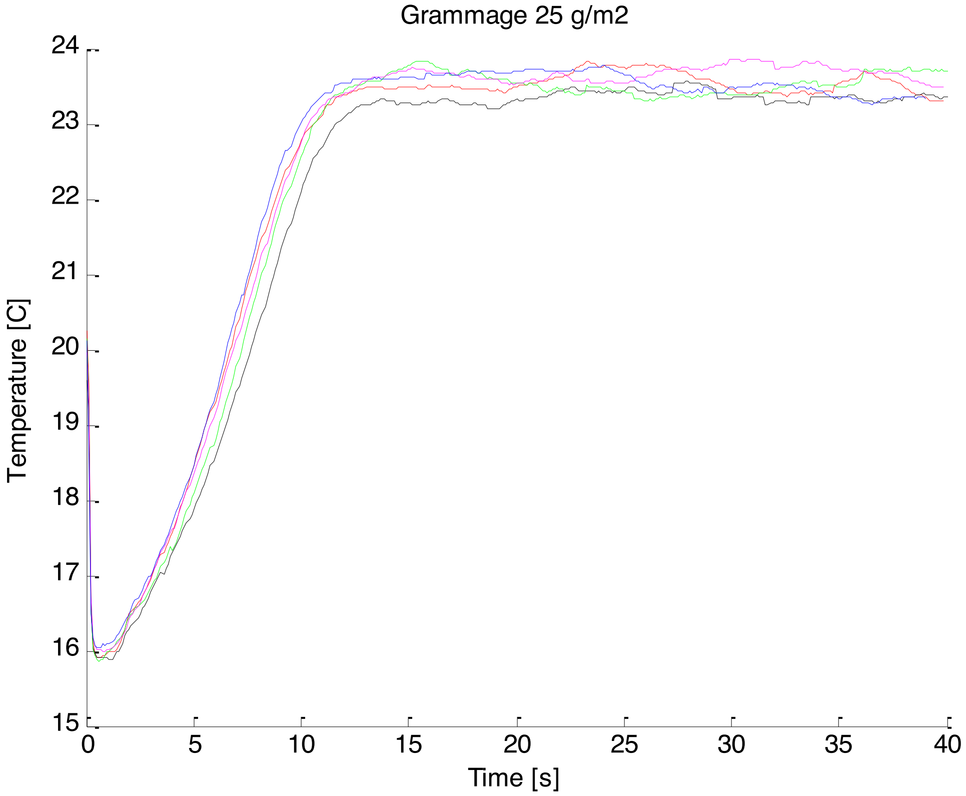


Figure 9. All trials for grammage 25g/m^2, mean temperature against time.

It can be seen that as the temperature stops increasing, it also started to fluctuate. The fluctuation, when studied closer, appears to lie within 0.5°C for all grammages. The fluctuation could also be seen in ThermoCAM^{TM}, and appears to stem from air of varying temperature swirling above the sample. The "swirl" is depicted in figure 10 below.

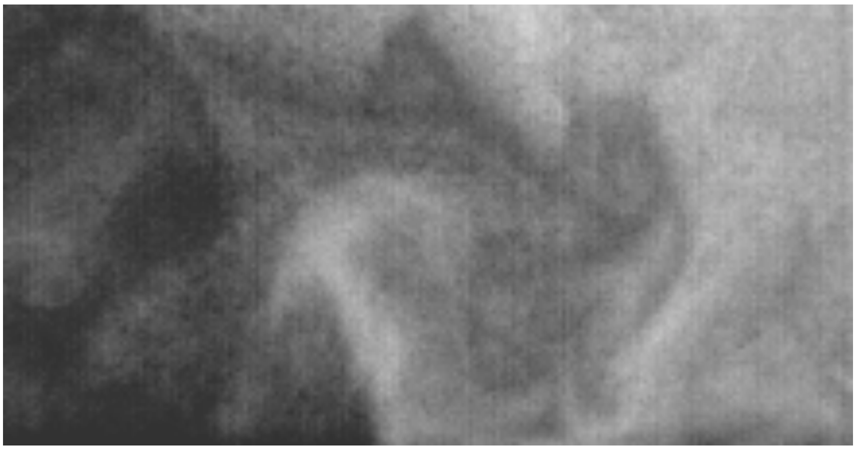


Figure 10. Depicting air "swirl" at time when sheet is dry.

A small change in at which temperature the temperature curve levels out was detected for the different samples of same grammage. These are within the measuring accuracy of the camera.

3.3.1 Temperature change using a different emissivity

To get an estimation of how much the temperature calculation changes with emissivity, emissivity was changed from 0.85 to 0.8 for the calculations for one sheet of grammage 15 g/m^2. The result is shown in figure 11.

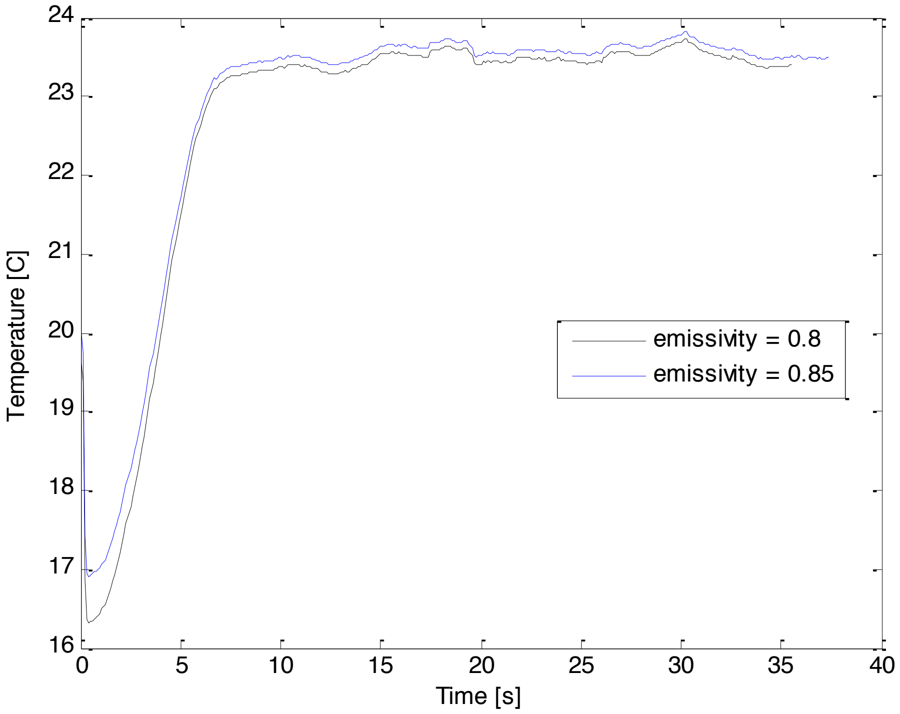


Figure 11. Variation in mean temperature over time using different values for emissivity.

Setting a lower value for the emissivity will result in a lower calculated temperature. For the minimum average temperature, the highest change in calculated temperature can be seen, with the temperature calculation decreasing by approximately 0.6°C. The change in calculated temperature with emissivity appears to be close to constant for all grammages. The difference between starting and minimum temperature increases by 0.2°C when the emissivity is lowered from 0.85 to 0.80. Changing the emissivity does not have an effect on at what time the temperature stops increasing.

3.4 Determining time for surface to dry

The sheet is considered to be dry when there is no longer an increase in temperature on the surface. However, the fluctuating temperature for the individual measurements made determining the time for when this occurred somewhat difficult. It also became a problem that not all trials reached exactly the same temperature before the temperature increase stopped. It was therefore decided to set a condition for drying time not dependent on an absolute temperature value.

As the temperature fluctuations appear to lie within 0.5°C for all grammages, this was used to determine drying time. A time was calculated for when the change in temperature was less than or equal to 0.5°C for a period of 10 seconds. Drying time for surface was then determined as the time 10 seconds previous to when this condition was fulfilled, that is by reducing the calculated time by 10 seconds. To prevent the drying time criteria to be fulfilled by the initial temperature, just before suction was applied, a criteria was also set that the time should be larger than one second.

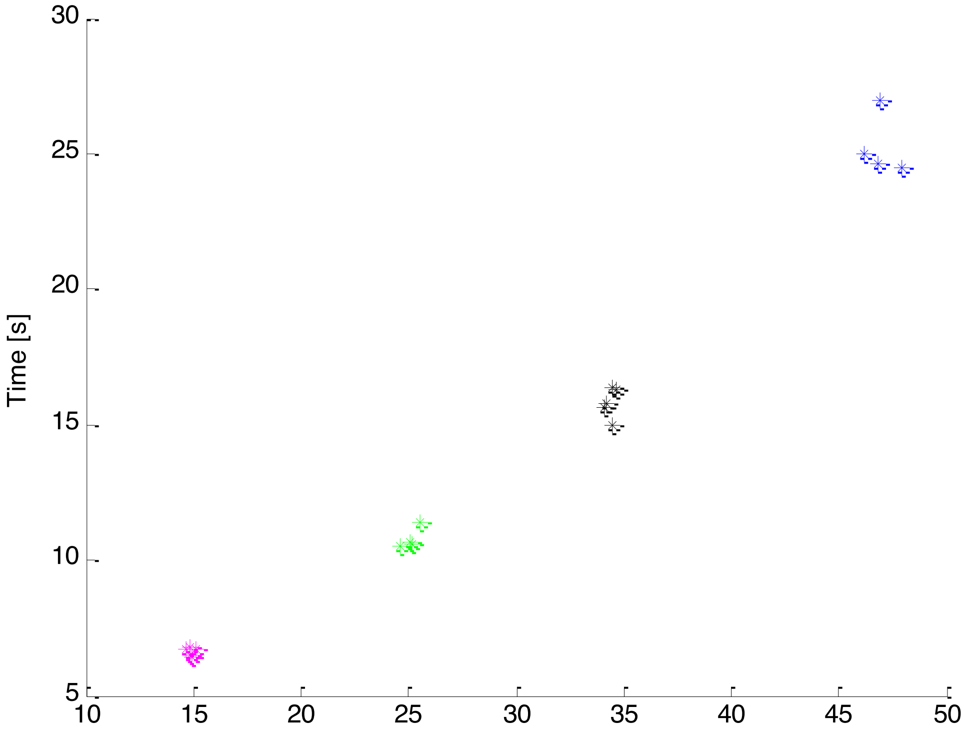


Figure 12. Mean drying times for sheets of varying grammage.

Performing the calculation for all sheets recorded gave the result in figure 12.

The time for the sheet to dry increases approximately five times as the grammage increases from 15 to 46 g/m^2. The paper is considered dry, in the sense that there is no longer a detectable change in the mean temperature over the sheet. There might still be local areas of the sheet that is not completely dry. Also, when comparing the values to the ones that can be estimated from figure 8 and 9, the calculated values are somewhat lower than those found by looking in the figures for when the curve panes out. This difference appears to increase with grammage, and becomes most apparent for the highest grammage 47 g/m^2.

The initial amount of moisture in the sheet will also affect the time of drying. Depicting drying time against this value showed the same trend as for grammage, as depicted in figure 13.

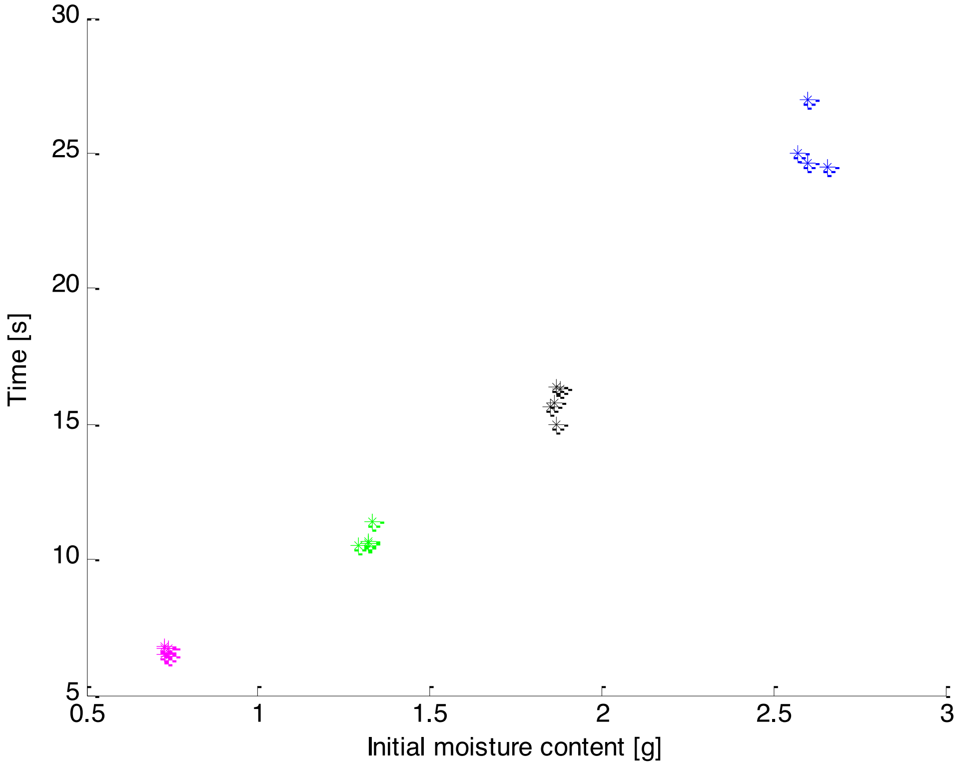


Figure 13. Mean drying time plotted against initial moisture content.

3.5 Variation of drying time over a surface

Since drying non-uniformity is to be investigated, it is of interest to see how the drying varies over the surface of a sheet. The previously set criterion for when the surface could be considered dry was now implemented for all elements of the sheet. This incurred a problem for the higher grammages 34 and 47 g/m^2. For these sheets, there existed areas that had such a slow increase in temperature that they fulfilled the criteria at a temperature clearly below that when the area could be considered dry. To minimize the effect of this, a temperature criterion was included and set so that the temperature of an area needed to exceed 21.5°C before being considered dry.

Drying time for the selected surfaces was calculated in MatLab, and the results given as a contour plot, where X and Y gives the location on the sheet, and a colour scale indicated the drying time. Extreme outliers were excluded if they only occurred in less than 10 elements of the matrix. The values of these outlying elements were set to approximately that of surrounding elements. An example for a sheet with grammage 15g/m^2 can be seen in figure 14.

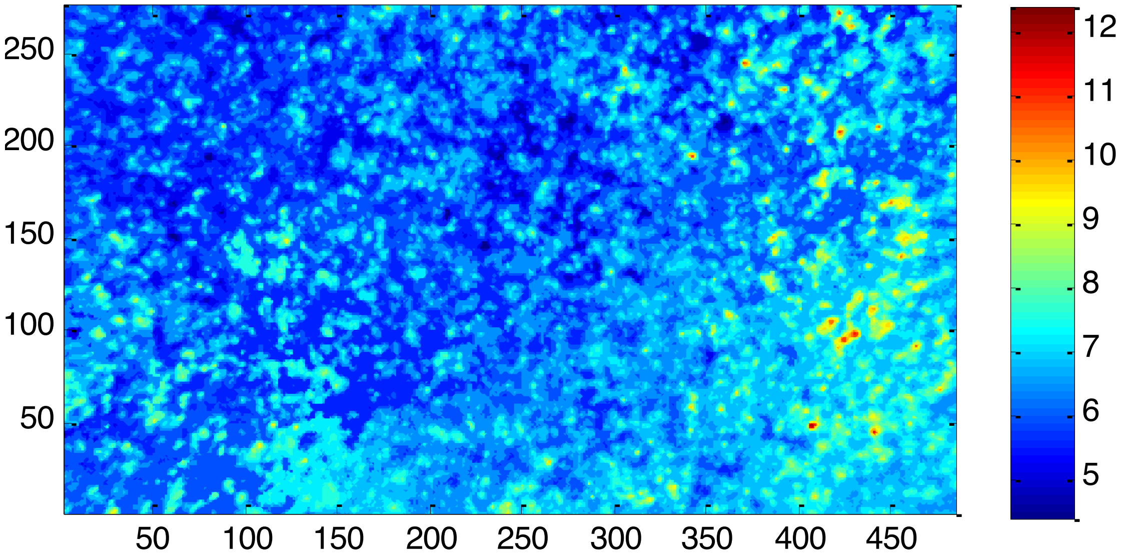


Figure 14. Variations in drying time for one sheet, grammage ~15g/m^2; shows position on x and y-axis and time as colour scale.

The results clearly indicate that there is a large variation in drying time across a sheet.

Since drying time is related to temperature, it is possible to see correlations between the ThemoCAM^{TM} image and the resulting MatLab plot giving drying times. An example of this can be seen in figure 15 below.

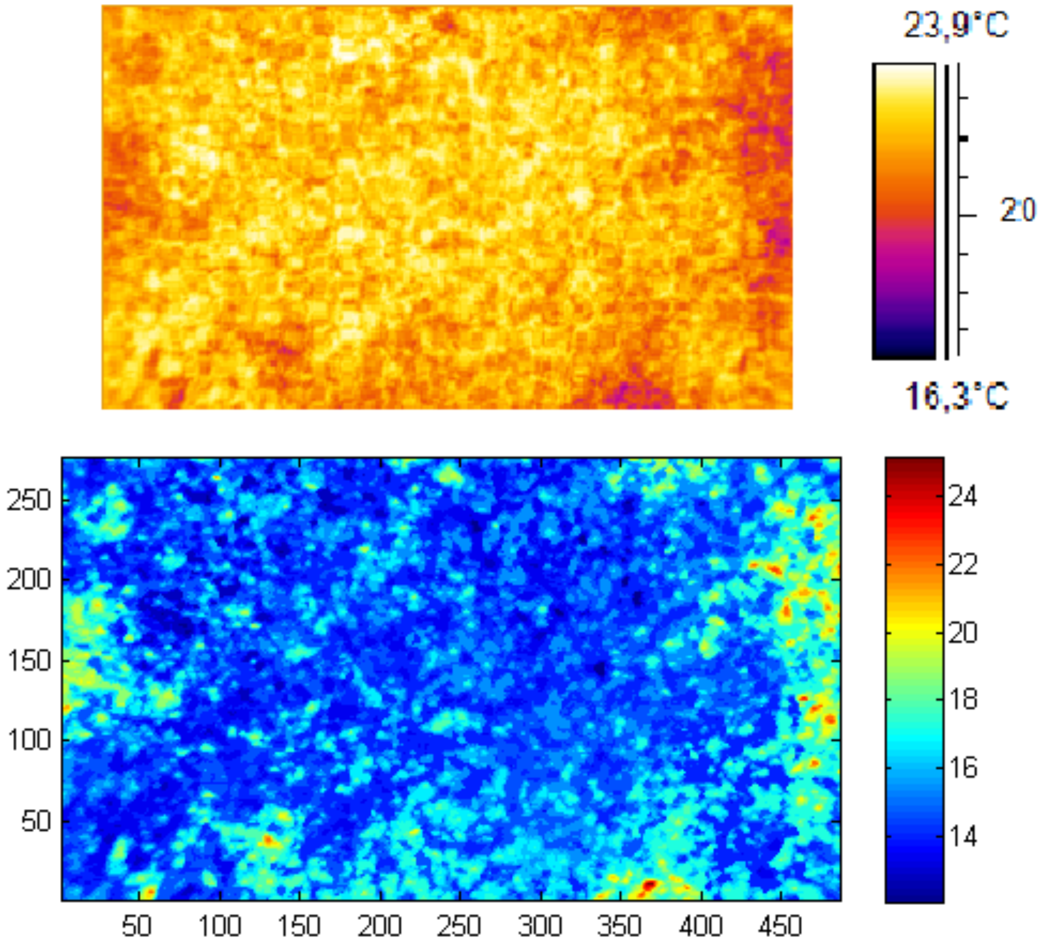


Figure 15. Temperature in the surface at a time during drying (12s) compared to final drying times over the sheet for whole area previously selected for analysis. Grammage ~34g/m^2.

This shows that the used MatLab routine appears to give a good indication of drying times for the selected part of the sheet.

Clear differences in local drying rates can be seen even when looking at sheets of same grammage, which can be seen in figure 16.

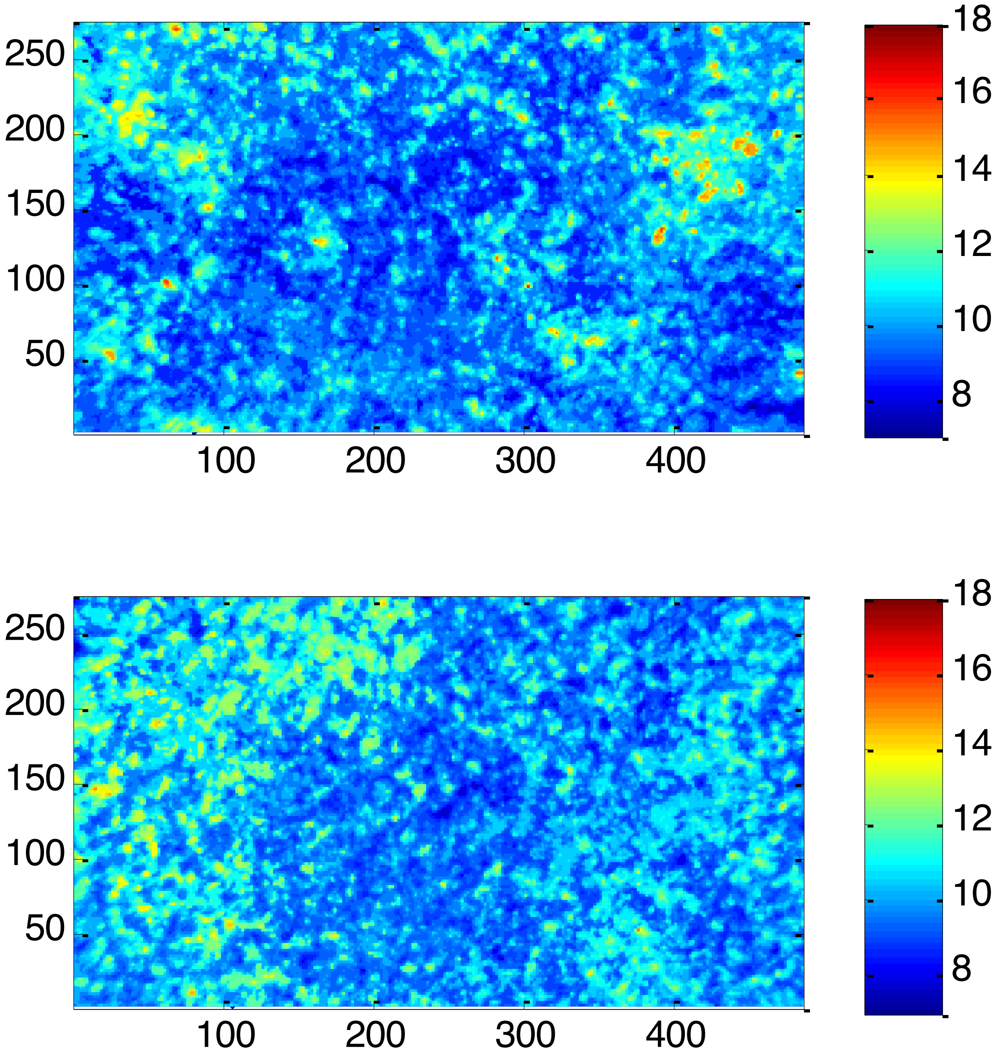


Figure 16. Drying times for two different sheets with grammage 25 g/m^2.

The MatLab routine was run for all sheets included in the trial, an overview of the results can be seen in table 6.

Table 6 Summary of results for different drying times across a sheet

Trial no	Grammage [g/m^2]	Drying Time min [s]	Drying Time max [s]	Mean drying time [s]	Std.Dev. [s]	T min [°C]	T max [°C]
10	14,84	4,4	12,8	6,6	0,72	22,4	23,5
11	14,8	4,6	14	6,5	0,81	21,7	23,9
12	15,06	3,8	12,1	6,4	0,73	22,3	23,8
13	14,73	4,5	13	6,4	0,9	22,4	23,8
14	14,88	4,5	12,1	6,4	0,65	22,5	23,9
5	25,12	7,2	20,1	10,2	1,27	21,9	23,7
6	25,45	8,3	19,8	11	1,11	22,3	23,6
7	24,6	6,8	15,8	10,5	0,9	22,4	23,6
8	25,23	7,4	15,5	10,4	1,05	21,7	24,1
9	25,45	7	17,9	10,1	1,1	22,8	23,7
15	34,53	9,5	27,7	15,3	1,9	22,5	24
16	34,2	12,1	25,8	15,5	1,37	23,3	24,3
17	34,67	11,3	25,2	15,6	1,94	22	23,9
18	34,45	10,6	24	14,8	1,3	22,7	24,2
19	34,05	10,1	25,3	15,1	1,6	22,9	24,3
1	46,2	18,3	44,7	24,1	3,27	21,6	23,7
2	46,9	16,7	45,2	24,4	3,05	21,9	23,6
3	47,86	18,3	44	23,3	2,35	22,3	24
4	46,8	17,6	46,9	23,8	2,21	22,4	23,5

The mean drying times calculated over the entire surface is in good correlation with the times calculated using the mean temperature of the sheet (figure13). Also, the minimum dry temperature does not appear to decrease with grammage.

When grammage increases, the difference between the highest and lowest calculated drying time increases. Also, there is a trend towards an increase in standard deviation with increased grammage, indicating that the drying becomes increasingly non-uniform.

Selecting trials 12, 6, 19, and 2, histograms were constructed to give a clearer picture of the drying time distribution for the selected grammages. These specific trials were selected since their standard deviation is closest to the average for the specific grammage. Results can be seen in figure 17.

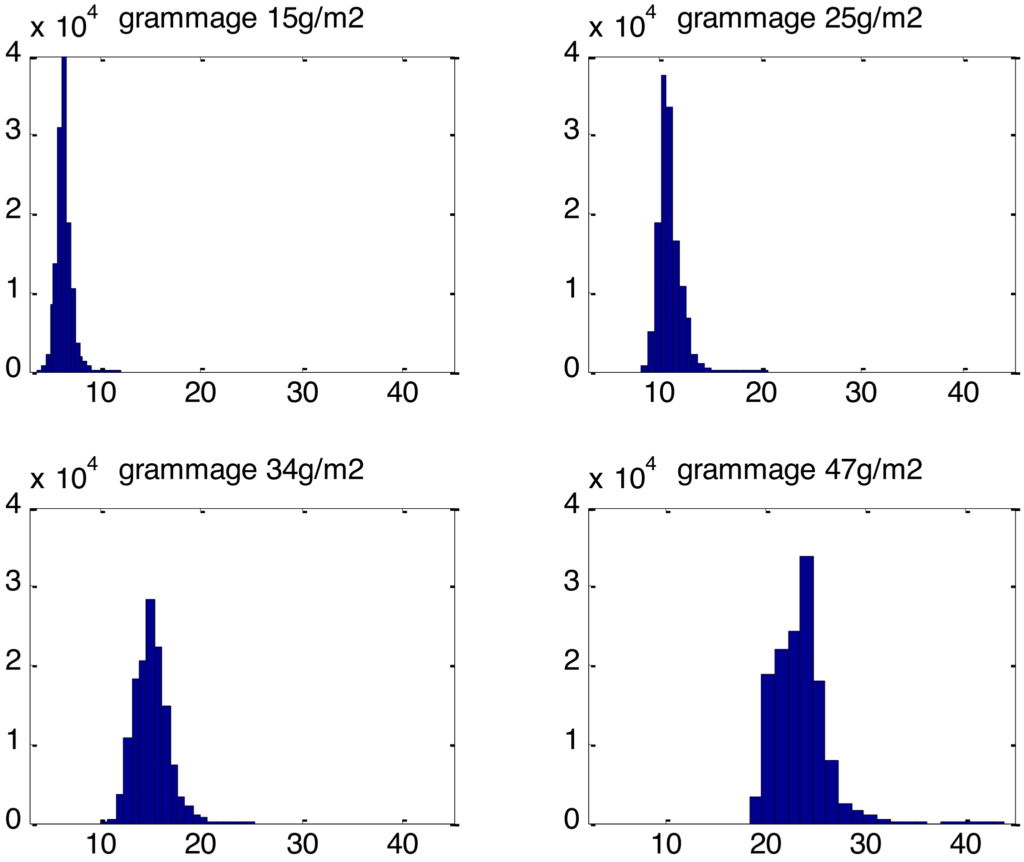


Figure 17. Histogram of drying time distribution over one sheet of each grammage. Shows time in seconds on x-axis and frequency on y-axis.

Due to the set criterion for temperature it is of interest to investigate how the drying time correlates to the temperature at which the sheet is considered dry. This is believed to have an effect especially on sheets with a higher grammage. In figure 18, the temperature for when the sheet could be considered dry is depicted together with the calculated drying time.

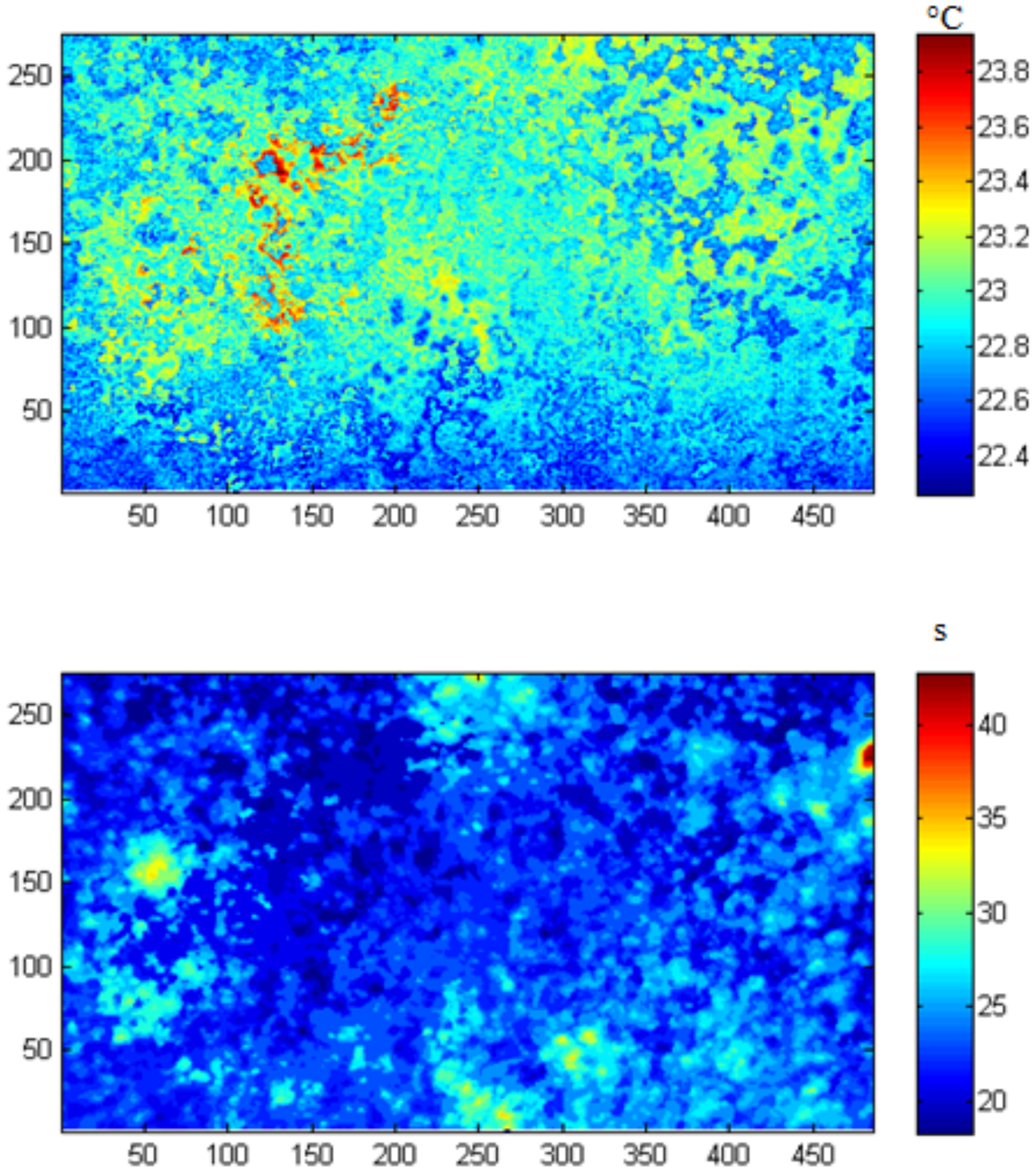


Figure 18. At which temperature the sheet is considered dry compared to calculated drying times across the sheet. Grammage ~47g/m^2.

No clear correlation can be seen between at which temperature an element was considered dry and the local drying time.

4 Discussion

4.1 Temperature change over time

The results obtained in this report indicated that for the specific pulp and grammages used, there exist no period of constant temperature. This could indicate that there is no period of constant drying rate, which is according to previous observations, stating that for low grammages no constants drying rate period needs to exist.

It can also be concluded that as the grammage increases, the calculated temperature reaches a lower point before starting to increase. This is somewhat surprising, since the permeability is higher for the sheets of lower grammage, it was believed that this would result in a higher air velocity through the sheet and therefore a higher drying rate and drop in temperature. The results acquired instead show that as the grammage increases, so does the drop in temperature.

The change could also in part depend on the set emissivity for the sheet. The sheet with a lower grammage has somewhat lower moisture content, and the emissivity should therefore have been set at a somewhat lower value. As was shown, for the existing conditions, the calculated temperature will decrease with emissivity. By lowering the emissivity, this would have resulted in a lower calculated temperature. Also, the sheet of the lowest grammage contains a lower amount of water, and behaves more like a screen than a packed bed. This will enhance the effect of setting the emissivity to high, since the fast drying time will give a quick increase in dry content for the sheet. The lower amount of water also makes it possible that the increase in temperature will start before the sheet reaches a low temperature.

In theory, lowering the emissivity was expected to result in an increased calculated temperature. However, for the set conditions the opposite was true. This may be due to evaporation during drying. The difference in calculated temperature for different emissivity increased as the temperature of the paper decreased. This could be expected, as the effect of the surroundings will have a greater impact on the calculated temperature as the temperature (signal) from the measured sheet decreases.

All measurements with the exception of those for 34 g/m^2 stabilize at close to the same temperature. Since all sheets were dried with air at room temperature, this shows that for these grammages the final moisture content at the sheet surface is approximately the same.

The exception to this trend was the measurements for 34g/m^2. Instead, these measurements levelled out at a value approximately 0.5°C higher. No reason for this deviation has been found, and it is therefore concluded that it must be due to a change in surrounding conditions. This highlights the importance of measuring the parameters set to evaluate data, such as reflected temperature, in particular when the conditions of the surroundings might change during experimentation.

The fluctuation in temperature as the sheet is dried is believed to depend on the conditions of the drying air. Since the air may have a variation in moisture content and therefore temperature, and is in motion, this gives a fluctuation in temperature.

4.2 Determination of time for drying

When looking at the average drying time, a clear difference can be seen for the different grammages. This is interesting, since non-uniformity in drying in part depend on the formation of the paper. The results show that for through air drying, the drying time increases with grammage for the same initial dry content.

In theory, the criterion for when a surface can be considered dry would be possible to set as when it reaches the temperature of the drying air. The fluctuation in temperature seen here made it difficult to determine at which temperature this occurred. Also, since the emissivity is set to a constant value for the drying process, this will as previously mentioned affect the calculated temperature. Using the criteria set in this report therefore has an advantage, since the time at which the temperature levels out is not dependent on an exact temperature.

In the study of drying of the sheet as a whole, the criterion set to determine when the sheet had dried was set as a change in temperature of less than 0.5°C over 10 seconds. Due to a slower change in temperature for the higher surface weight, this leads to the drying time for these sheets to be underestimated. The difference between the actual drying time and the estimated time increases when the slope of the temperature curves declines, which is when grammage increases. Using temperature as a criterion for determining dryness could help decrease the impact of this. Determining at which temperature this criteria should be set is however difficult, and when looking at the average for the selected part of the sheet, it was decided not to set temperature as a criterion.

When looking at the drying times for local elements in the sheet, the previously set criterion was not sufficient. There is a slower temperature change for higher grammages, resulting in local areas of the sheet with a high moisture content having a very low rate of temperature change. This leads to this area fulfilling the previously set criterion even though the specified area is not dry.

Comparing the previously determined mean drying time to the one given by the one found when looking at all elements in the sheet, show a good correlation between the calculations. This indicates that the temperature criteria imposed does not have a large effect on the calculated drying times. Also, when looking at the temperature at which an element of the sheet is considered dry, no clear correlation can be seen between this temperature and the calculated drying time.

When looking at standard deviation for the drying rates across a sheet, it is indicated that the non-uniformity of drying increases with grammage. Also, the time span between the minimum drying time and maximum drying time for one sheet increases from approximately 10 to 25 seconds when grammage increased from 15g/m^2 to 47 g/m^2.The sheets used in this trial were laboratory sheets, which have a good formation. Therefore, in a “real” paper, it is likely that the variations will be even higher.

4.3 Temperature and pressure drop

In industrial production, paper is dried using hot air at 150-250°C. During these trials, air was at room temperature and the pressure drop low, which gives a long drying time. This will probably affect the results when compared to industrial settings. It is however difficult to say exactly how this will affect the drying process compared to industrial conditions.

For this project, the sheet was considered dry when the surface temperature had stabilized at a temperature close to the surrounding temperature. Since air is sucked through the fibre web, there will exist a moisture profile in the paper, and there may be variations in the z-direction. Therefore, it could be interesting to determine how much moisture remains in the sheet when the surface has dried, since this may indirectly have an effect on the surface temperature. However, since this study only included sheets of a very low grammage, it is believed that the moisture profile across the sheet will be small.

For the experimental setup used in this report, there existed no possibility to control or measure air flow and pressure drop during a trial. It is believed that for the sheets of higher grammage, the pressure drop will increase and net-air flow decrease. As the sheet dries, the permeability will increase, causing the pressure drop to decrease and therefore the net-air flow to increase.

5 Conclusions

Using an infrared thermo camera, documentation of the drying of sheets with different grammage through TAD has been conducted. By studying the sheet surface, a clear variation in temperature could be detected. The method used gives a clear indication of variations in drying time for sheets of different grammage, and also for variations in drying uniformity across one sheet.

The change of emissivity during drying will affect the calculated temperature, and makes it difficult to determine an exact temperature at which the sheet can be considered dry. Not using temperature as a criterion makes it possible to compare sheets of varying initial moisture content.

Results acquired also indicated possible problems with the method, since variations in temperature across the surface due to air flow were observed at the end of drying. This made it difficult to determine an exact point at which the temperature of the sheet stabilized, and may result in the criteria used underestimating the time of drying for higher grammages.

The results showed that the minimum average temperature for the sheet decreases as grammage increases. It also showed a clear increase in drying time as the grammage increased. The drying non-uniformity across a sheet increased with grammage, giving an increase in time span between minimum and maximum drying time from 10 seconds for 15g/m^2 to 25 seconds for 47g/m^2.

6 Future work

The results of this study showed that the average minimum temperature a sheet reached during drying decreased with an increase in grammage. It was however difficult to determine what could be the cause of this. For future studies, it would be of interest to look further into this and determine possible causes.

For this project, the sheet was considered dry when the surface temperature had stabilized at a constant temperature. Since air is sucked through the fibre web, there may exist a moisture profile in the paper and variations in z-direction. Therefore, for future studies the actual moisture content in the sheet when the surface is considered dry should be determined.

Neither air flow nor pressure drop was controlled in this study. For future trials, a way to measure or control these parameters should be constructed. To get a higher accuracy when comparing results between trials, one of these parameters should be held at a constant value.

The fluctuation in temperature when a sheet is considered dry is believed to stem from variations in the drying air. It is therefore recommended that the equipment be placed in an environment where the conditions of the drying air can be controlled.

As mentioned previously, the method will in future studies be used to investigate the influence of other material properties on the non-uniformity of drying. These include raw material, pulp treatment, sheet structure, grammage and grammage non-uniformity on the dewatering efficiency.

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Contact through e-mail 2012-05-16

Appendix A

Tables containing results used to determine grammage and initial moisture content.

Table 7 Grammage of sheets from recorded trials

Trial no.	Weight dry sheet [g]	Grammage [g/m2]	Moisture content*
1	1,26	46,24	2,57
2	1,28	46,91	2,60
3	1,30	47,86	2,66
4	1,27	46,80	2,60
5	1,18	43,42	2,41
		46,24	2,57
6	0,68	25,12	1,32
7	0,69	25,45	1,33
8	0,69	25,45	1,33
9	0,69	25,23	1,32
10	0,67	24,61	1,29
		25,18	1,32
11	0,40	14,84	0,73
12	0,40	14,80	0,73
13	0,41	15,06	0,74
14	0,40	14,73	0,73
15	0,41	14,88	0,74
		14,86	0,74
16	0,94	34,53	1,87
17	0,93	34,20	1,86
18	0,94	34,67	1,88
19	0,94	34,45	1,87
20	0,93	34,05	1,85
		34,38	1,87

*Moisture content estimated using mean from previously measured wet sheets. (see table 4 above)

Table 8 Measurements to determine initial moisture content

Wet sheet [g]	Dry sheet [g]	Dry content [%]	Moisture content [g]	Grammage [g/m2]
1,15	0,41	0,357	0,74	15,06
1,17	0,42	0,354	0,76	15,28
1,15	0,41	0,352	0,75	14,88
1,16	0,41	0,355	0,75	15,17
1,15	0,41	0,356	0,74	15,06
		0,355	0,75	15,09
1,94	0,66	0,342	1,28	24,39
1,99	0,68	0,342	1,31	24,98
1,90	0,65	0,341	1,25	23,80
2,00	0,69	0,343	1,32	25,23
2,00	0,68	0,343	1,31	25,12
		0,342	1,29	24,71
2,82	0,95	0,335	1,88	34,71
2,85	0,95	0,335	1,89	35,04
2,83	0,95	0,335	1,88	34,86
2,75	0,92	0,333	1,83	33,61
2,86	0,95	0,332	1,91	34,93
		0,334	1,88	34,63
3,65	1,20	0,328	2,45	43,97
3,81	1,26	0,332	2,54	46,39
3,64	1,19	0,327	2,45	43,75
3,92	1,28	0,327	2,64	46,98
3,93	1,29	0,329	2,64	47,46
		0,329	2,54	45,71

Table 9 Change in temperature, deltaT for individual trials.

Trial no	Grammage [g/m2]	T min [°C]	Tdry [°C]	deltaT [°C]
10	14,84	16,9	23,6	6,7
11	14,80	16,9	23,6	6,7
12	15,06	16,8	23,7	6,9
13	14,73	17,0	23,6	6,6
14	14,88	17,0	23,5	6,5
5	25,12	16,0	23,5	7,5
6	25,45	15,9	23,4	7,5
7	24,60	15,9	23,5	7,6
8	25,23	16,0	23,5	7,5
9	25,45	16,0	23,7	7,7
15	34,53	16,2	24,0	7,8
16	34,20	16,4	23,8	7,4
17	34,67	16,1	23,9	7,8
18	34,45	16,2	23,8	7,6
19	34,05	16,3	24,0	7,7
1	46,20	15,1	23,2	8,1
2	46,90	15,3	23,4	8,1
3	47,86	15,3	23,5	8,2
4	46,80	15,5	23,5	8,0

Appendix B

MatLab routines implemented to evaluate results.

MatLab routine 1

```
%Routine to plot mean temperature against time

clear all
clc
hold on

matFiles = dir('*.mat');
L=length(matFiles);

Tstart=0;


for k = 1:430

  namestr=strcat('Film',num2str(k));

  load(namestr)
  %Recalculated temperature from K to C
  I=(eval(namestr)-273.15);

  %Gives time vector for current file
  Tid=strcat('Film',num2str(k),'_DateTime');
  T=(eval(Tid));


  T1(k)=(T(4)*3600)+(T(5)*60)+T(6)+(T(7)/1000);
  %Calculate average for selected part of matrix
  Medel(k)=mean2(I(170:450,80:566));

  %Setting criteria to stop loop
  if Tstart==0;
    %Setting criteria for when air flow started
    if k>=2 && ((Medel(k)-Medel(k-1))/(T1(k)-T1(k-1)))<=(-1)
        Tstart=T1(k-1);
        a=k-1;
    end
  end

  %Calculating time since air flow started
  Tidaktuell(k)=T1(k)-Tstart;

end

%Get plot to start from 0
Tidaktuell(a)=T1(a)-Tstart;
plot(Tidaktuell(a:L),Medel(a:L),'b-');
```

MatLab routine 2

```
%Routine gives mean time for grammage for specified sheet


clear all
clc

matFiles = dir('*.mat');
L=length(matFiles);

Tstart=0;
A=0;




for k = 1:L

  namestr=strcat('Film',num2str(k));

  load(namestr)
  %Gives elements in matrix in C instead of K
  I=(eval(namestr)-273.15);

  %Time vector for current measurements
  Tid=strcat('Film',num2str(k),'_DateTime');
  T=(eval(Tid));

  T1(k)=(T(4)*3600)+(T(5)*60)+T(6)+(T(7)/1000);
  %Calculated average temperature for selected area
  Medel(k)=mean2(I(170:450,80:566));

 %Gives time for start of air flow
  if Tstart==0;
    if k>=2 && ((Medel(k)-Medel(k-1))/(T1(k)-T1(k-1)))<=(-1)
        Tstart=T1(k-1);
        a=k-1;
    end
  end

  %Time since start of trial (air flow
  Tidaktuell(k)=T1(k)-Tstart;

 if Tstart~=0
  if A==0
     if k>=101+a+10 && abs(Medel(k)-Medel(k-100))<=0.5 &&
(Tidaktuell(k)-Tidaktuell(k-100))>=10
         %Criteria set to stop loop when reached a drying time
         A=A+1;
         Torktid=Tidaktuell(k)-10
     end
  end
 end
```

```
end
```

MatLab routine 3

```
%Routine gives the drying times for all elements in the matrix, the
%variations in drying time across one sheet

clear all
clc

matFiles = dir('*.mat');
L=length(matFiles);


Tstart=0;
Torktid(1:276,1:486)=0;
Torktemperatur(1:276,1:486)=0;

%Loading all files in the selected recording
for k=1:L
   namestr=strcat('Film',num2str(k));

  load(namestr)
end

%Due to computer limitations, an extra loop needed to be introduced to
give
%the complete sheet matrix
for w=1:6
for v = 1:6

    A(1:46,1:81)=0;

for k=1:L

  namestr=strcat('Film',num2str(k));
  I=(eval(namestr)-273.15);

  %Area of sheet selected for analysis containing temperaure data
  B=I(170+(v-1)*45+(v-1):170+v*45+(v-1),80+(w-1)*80+(w-1):80+w*80+(w-
1));

  %Gives time vector for current file
  Tid=strcat('Film',num2str(k),'_DateTime');
  T=(eval(Tid));

  %Recalculating time vector into seconds
  T1(k)=(T(4)*3600)+(T(5)*60)+T(6)+(T(7)/1000);
  Medel(k)=mean2(I(170:450,80:566));

  %Criteria set to stop loop after iteration
```

```
  if Tstart==0;

      %Setting criteria for when air flow starts
    if k>=2 && ((Medel(k)-Medel(k-1))/(T1(k)-T1(k-1)))<=(-1)
        Tstart=T1(k-1);
        a=k-1;
    end
  end

  %Calculating time since air flow was started
 Tidaktuell(k)=T1(k)-Tstart;

if Tidaktuell(k)>=0


    for i=1:46
        for j=1:81;
            if A(i,j)==0
               Tiden(i,j,k)=Tidaktuell(k);
               Temperatur(i,j,k)=B(i,j);

                    %Setting criteria for when element of the sheet is
                    %considered dry.
                    if Tstart~=0  && B(i,j)>=22 && k>=101+a+10 &&
abs(Temperatur(i,j,k)-Temperatur(i,j,(k-100)))<=0.5 &&  (Tiden(i,j,k)-
Tiden(i,j,(k-100)))>=10                       A(i,j)=A(i,j)+1;
                        %Saving temperature and time for when sheet is
                        %considered dry
                        Torktid(277-i-(v-1)*45-(v-1),j+(w-1)*80+(w-
1))=Tiden(i,j,k-100);
                        Torktemperatur(277-i-(v-1)*45-(v-1),j+(w-
1)*80+(w-1))=Temperatur(i,j,k-100);
                    end

            end
        end

    end
end


end
end
end




%Creating contour plot
contourf(Torktid,20,'EdgeColor','none','LineStyle','none')
%Scaling of axis
axis image;
```