

THERMAL CONDUCTIVITY OF HANDSHEETS, PAPERS AND MODEL COATING LAYERS

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ABSTRACT

Thermal conductivity of paper is a property of importance in the understanding of conductive heat transfer in the pulp and paper industry. For example, heat transfer between a paper web and a heated roll in a nip during calendering. Besides, the trends in the calendering area are to replace machine calenders by soft calenders and to replace cotton filled rolls by polymeric rolls in the supercalenders. As a result, temperatures of heated rolls in calenders are increasing constantly. There is a need for measuring thermal conductivity of paper. Some measurement methods and some values of thermal conductivity are available in the literature. But measurement methods are often reserved to specialists and values of conductivity show great variations. This drove us to develop a rapid method to measure the thermal conductivity of semi-insulated films. Our objective was to be able to measure the thermal conductivity of papers, of polymers and of model coating layers—with simplicity and rapidity, if necessary at the expense of the accuracy. Indeed heat transfer calculations often used a lot

of restrictive hypotheses and a measurement of the thermal conductivity with an accuracy of less than 10% is quite sufficient.

MEASUREMENT DEVICE

Introduction to the device

The measurement device was conceived by the CSTB (Centre Scientifique et Technique du Batiment) based on a paper of Lee [1] and was developed by the CTP (Centre Technique du Papier). The measurement principle is quite simple: a sample, laid on a hot plate, is maintained to a constant temperature (T_1). A mass is suddenly put in contact with the sample. The initial temperature of the mass (T_0) is lower than T_1 . The evolution of the temperature of the mass during time depends on the thermal conductivity of the sample.

Samples are a pile of 19 mm in diameter disks, whose global thickness must be between 100 μm and 800 μm . Thermal conductivity of samples must be between

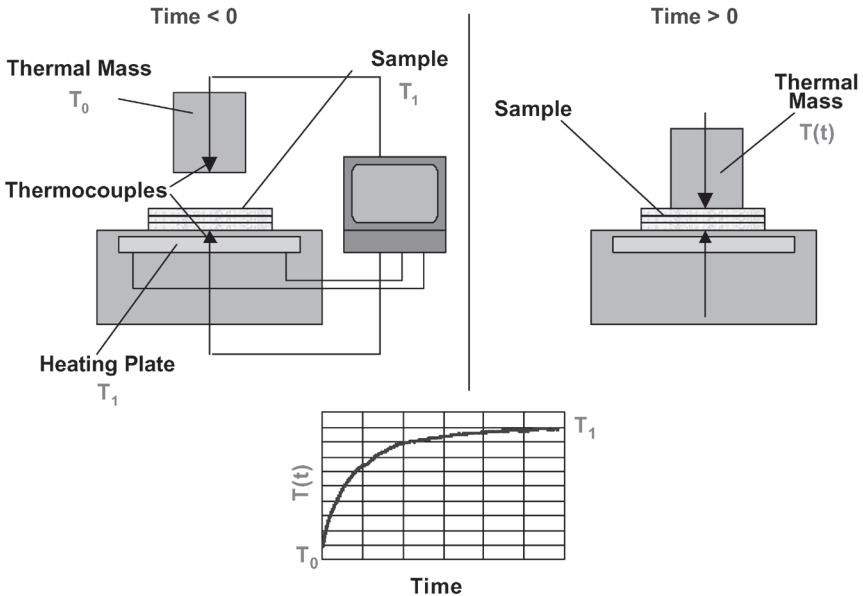


Figure 1 Diagram of the device.

lower than 1.5 W/m.K for a valid measurement. The thermal mass is applied to samples under a pressure of about 100 kPa.

The temperature of the heated plate is about 40–45°C and the initial temperature of the mass is about 5°C lower. These temperatures are chosen to avoid vaporisation of water from paper samples and to avoid creating an excessive humidity gradient in the thickness direction of the paper sample.

The main limits of this device are:

- It is not possible to make the temperature vary on a large range of values.
- It is not possible to make pressure variations.

Theoretical principle, data treatment

The measuring cell was modelled from a thermal point of view. From this theoretical study, the following conclusions can be drawn:

- The temperature curve of the thermal mass follows a first order exponential law.
- There are contact thermal resistances between the heated plate and the sample, between the sample and the thermal mass, and between the sample disks. The first two cannot be dissociated.
- The convective heat losses from the lateral surface of the sample can be neglected.
- The convective heat losses from the lateral and top surfaces of the thermal mass have to be taken into account. These losses can be expressed in terms of a single convective resistance given by a Biot number.
- The following equation describes the evolution of the temperature of the non heating mass during the measurement:

$$T(t) = T_0 + \frac{T_1 - T_0}{1 + Bi} \cdot \left(1 - \exp\left(-\frac{(1 + Bi) \cdot t}{\tau}\right) \right) \quad (1)$$

Where $T(t)$ is the non heating mass temperature versus time t

T_0 is the initial temperature of the thermal mass

T_1 is the temperature of the heated plate

Bi is the Biot number representing the convective heat losses from the thermal mass

τ is the time constant of the exponential law

The theoretical curve given by Equation 1 fits quite well with the collected data. It is therefore possible to evaluate the time constant and the Biot number of our system for each measurement. Besides, the total thermal resistance

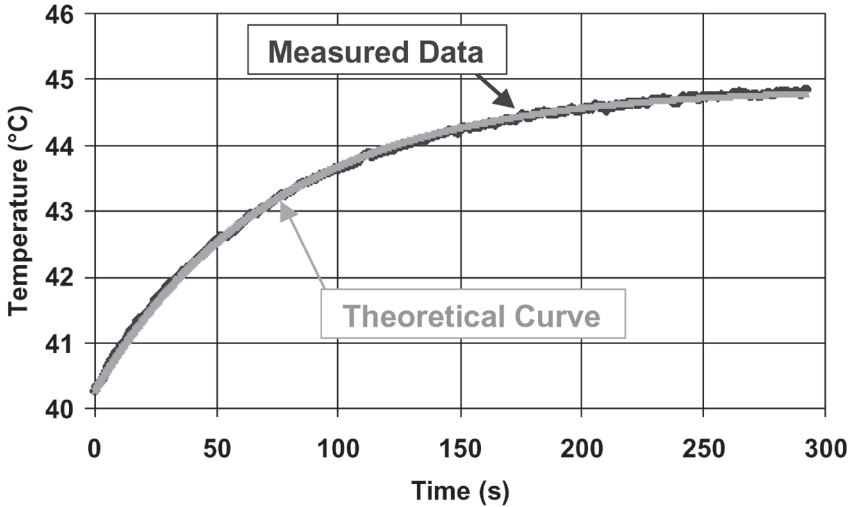


Figure 2 Temperature of the thermal mass versus time. Comparison between the collected data and the theoretical curve.

of the sample R_{th} (including contact thermal resistances) depends on the time constant of the system by the following equation:

$$R_{th} = \frac{S \cdot \tau}{C} \quad (2)$$

Where S is the contact surface between the non heating mass and the sample
 C is the heat capacity (in $J/^\circ C$) of the thermal mass
 τ is the time response of the system

For a n sample disk stacking, this thermal resistance can be divided into three parts. The first one is due to the thermal resistance of the sample (it corresponds to a true or an intrinsic conductivity), the second part is due to the thermal resistance of contacts between the sample disks and the third part is due to the contact resistance between the stack and the metallic parts of the device (i.e. between the samples and the heating plate and the samples and the thermal mass):

$$R_{th} = R_{sample} + (n - 1) \cdot R_{contact\ sample} + R_{contact} \quad (3)$$

To evaluate the importance of the contact resistance between two sample disks, we have to compare the thermal resistance of a several sheet stack with the thermal resistance of a single sheet sample having the same thickness.

Thus handsheets were made from a blend of pulp (75% of softwood sulphite pulp and 25% of eucalyptus pulp).

The first series of sample is made up of six handsheets with a varying thickness (165, 295, 414, 545, 666, 798 μm), the second series is made up of six handsheets whose thickness are comprised between 130 μm and 165 μm . The stacking of the second series handsheets leads to stack of the following thickness: 165, 304, 423, 547, 672 and 801 μm .

The measurements of thickness and thermal conductivity were done under normalised conditioning (23°C and 50% HR).

The following figure exhibits the thermal resistance of the stack versus the thickness of the stack for the two series described formerly.

The slight difference observed between the two series on the Figure 3 shows that the contact resistance between the sample disks can be disregarded. Thus, Equation 3 becomes Equation 4:

$$R_{th} = R_{sample} + R_{contact} \quad (4)$$

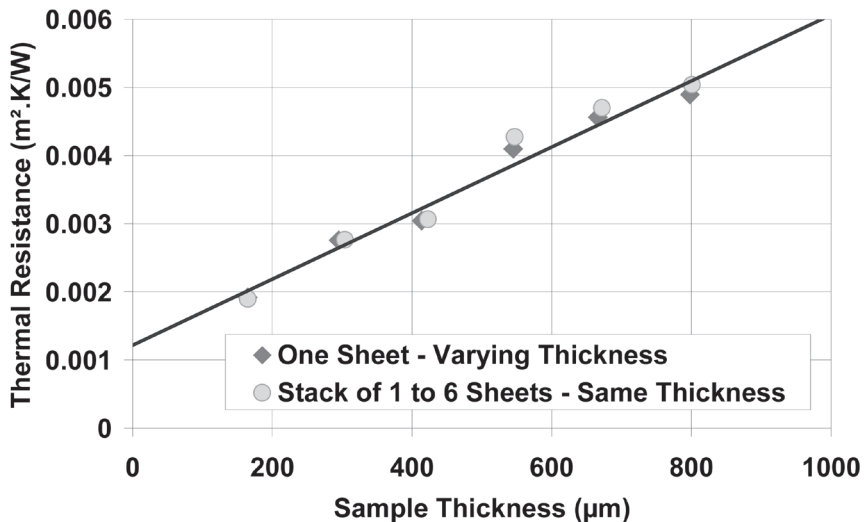


Figure 3 Thermal resistance of handsheets versus thickness of the pile of samples.

R_{sample} is the true thermal resistance of the sample.

$R_{contact}$ is the contact resistance between the sample and the metallic parts of the measuring device.

Theoretically R_{sample} is a linear function of the thickness of the sample and $R_{contact}$ is independent of the thickness of the sample and is the intercept of the fitted straight line drawn on Figure 3. The inverse of the slope of this fitted straight line is the true thermal conductivity of the material. This method is used afterwards to calculate the thermal conductivity. To sum up, to measure the thermal conductivity of thin semi-insulated films, a four step method is used:

- Firstly, we make a pile with several layers of the material to be measured.
- Secondly, for each thickness of the pile, we calculate a time of response (and thus a thermal resistance) of our system from the measurements of temperatures;
- Thirdly, we fit a straight line between the thermal resistances and the thickness of the piles;
- Finally, we calculate the thermal contact resistance from the intercept of this straight line with the y-axis and we calculate the intrinsic thermal conductivity of the material from the slope of this regression straight line.

Validation of the device, accuracy of the measurement

To validate the measuring device, we made some measurements on polymeric materials: polyvinyl chloride, polyethylene, polypropylene and mylar. Then, we compared our values with those found in the literature and with values measured by a flash diffusivity method.

We can note that the tested polymers are commercial and we don't know the nature and the amount of fillers that they could contain. The values of conductivity of these materials are given in Table (1).

Table 1 Thermal conductivity (W/m.K) measured and given by the literature for various polymers.

	Polyvinyl Chloride	Polyethylene	Polypropylene	Mylar
CTP Measurements	0.18	0.47	0.18	0.21
Literature	0.16 ⁽²⁾ –0.21 ⁽³⁾	0.42–0.52 ⁽³⁾	0.12–0.20 ⁽³⁾	0.14–0.22 ⁽¹⁾
Measurements by flash diffusivity	0.16			

Table 1 shows that our values are at the upper end of the range given by the literature. However the samples are not the same. Furthermore in the literature the values often included a contact resistance, which lowers the conductivity value. Thanks our device, we can obtain separately a true thermal conductivity and a contact thermal resistance. Repeatability and reproducibility tests, carried out on paper handsheets and polymer films, showed an accuracy of about 0.01 W/m.K.

MODELLING OF THERMAL CONDUCTIVITY OF POROUS MATERIALS

Considering a porous material, it is sometimes interesting to be able to calculate the thermal conductivity of the material from the thermal conductivity of the solid phase, from the thermal conductivity of the gaseous phase and from structural parameters.

The simplest modelling, is a plate-like modelling which requires only the thermal conductivity of the different phases and their proportions by volume. Plates represent each phase.

Thus, there are three cases:

Either the plates are parallel to the direction of the heat flow (Figure 4, parallel model), or the plates are orthogonal to the direction of the heat flow (Figure 4, series model), or the two situations are mixed (Figure 4, hybrid model).

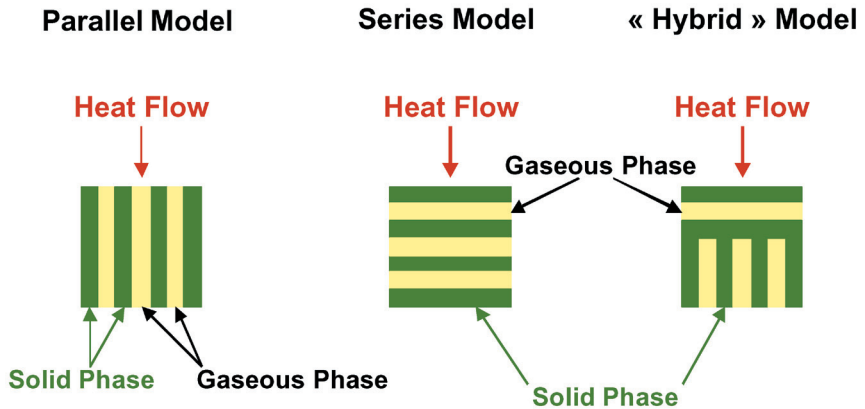


Figure 4 Three simple models for porous materials.

If K_S is the thermal conductivity of the solid phase,
 K_G is the thermal conductivity of the gaseous phase,
 γ is the fraction in volume of the gaseous phase,

then, the thermal conductivity (K_I) of the material arranged in a parallel model structure is:

$$K_I = (1 - \gamma) K_S + \gamma K_G \quad (5)$$

and the thermal conductivity (K_{II}) of the material arranged in a series model structure is:

$$K_{II} = \frac{1}{\frac{(1 - \gamma)}{K_S} + \frac{\gamma}{K_G}} \quad (6)$$

If the contribution (fraction in volume) of the parallel model to the hybrid model is a , then the contribution of the series model structure is $1-a$, then the thermal conductivity (K_{III}) of the material arranged in this hybrid model structure is:

$$K_{III} = \frac{1}{\frac{a}{K_I} + \frac{(1 - a)}{K_{II}}} \quad (7)$$

From a physical point of view, the parallel model means that there is a continuous way in each phase for the heat to be conducted from one side of the material to the other.

On the contrary, the series model structure means that there is no possibility for the heat to go across the material without changing phase. The hybrid model is a compromise between these two situations.

THERMAL CONDUCTIVITY OF SOME PULPS AND OF A BLEND OF PULP

Handsheets of three different pulps and of a blend of these pulps were made. We measured their basis weight, their thickness and their thermal conductivity. We also calculate their bulk and their porosity. The results are given in Table 2.

Table 2 Thermal conductivity of handsheets made from different pulps or blend of pulps.

Kind of pulp	Softwood bleached kraft pulp (Cellulose)	Deinked pulp (DIP)	Thermo-mechanical pulp (TMP)	Blend 27.5% Cellulose 14.5% DIP 58% TMP
Basis weight (g/m ²)	62.2	54.7	59.6	54.4
Bulk (cm ³ /g)	1.70	1.88	2.28	2.00
Porosity (%)	62	65	72	68
Handsheets thermal conductivity (W/m.K)	0.17	0.10	0.18	0.15

On this table, it appears that the handsheets made of deinked pulp lead to lower values of thermal conductivity than the handsheets made of softwood bleached kraft pulp and those made of thermomechanical pulp. The handsheets made of the blend of these three pulps give a value of conductivity between the highest value and the lowest value that we measured with the handsheets made of a single pulp. Since all the handsheets have values of porosity that are close, the differences seem to depend on the nature of the pulp.

We used the parallel model in a reverse way to calculate the thermal conductivity of fibres from the thermal conductivity of air (0.026 W/m.K), the thermal conductivity of the handsheets and the porosity (ϵ):

$$K_{fibres} = \frac{K_{handsheet} - \epsilon \cdot K_{air}}{1 - \epsilon} \quad (8)$$

The values of thermal conductivity of fibres show greater differences than those observed on handsheets.

For the blend of pulp, it is of interest to find a way to calculate the thermal conductivity of the handsheet from the thermal conductivity of the pulps and the porosity.

We assume that the thermal conductivity of the fibrous part of the blend can be calculated from the thermal conductivity of the fibrous part of each kind of fibre, their proportion in the blend (in volume) and a series model structure.

Then we used the parallel model structure to calculate the thermal conductivity of the handsheet from the thermal conductivity of the fibrous

Table 3 Recalculated thermal conductivity of fibres.

Kind of pulp	Softwood bleached kraft pulp (Cellulose)	Deinked pulp (DIP)	Thermo-mechanical pulp (TMP)	Blend 27.5% Cellulose 14.5% DIP 58% TMP
Recalculated fibre thermal conductivity (W/m.K)	0.40	0.24	0.57	0.42

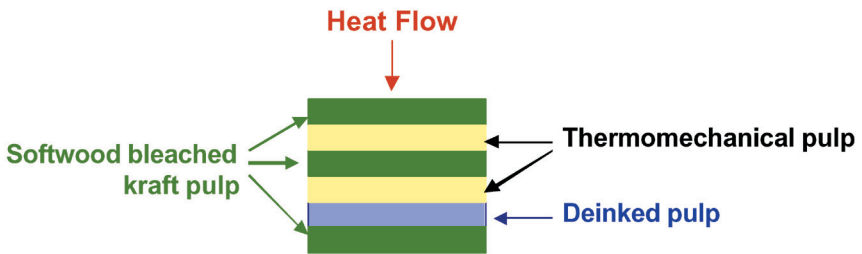


Figure 5 A series model structure applied to the fibrous phase of a handsheet made of a blend of pulps.

phase, the thermal conductivity of air and the porosity. This leads to the following Equation:

$$K_{handsheet} = \varepsilon \cdot K_{air} + \frac{(1 - \varepsilon)}{\frac{\chi_{TMP}}{K_{TMP}} + \frac{\chi_{DIP}}{K_{DIP}} + \frac{\chi_{Cellulose}}{K_{Cellulose}}} \quad (9)$$

Where $K_{handsheet}$ Thermal conductivity of the handsheet made from the blend of TMP, DIP and cellulose,
 K_{air} Thermal conductivity of air (0.026 W/m.K),
 K_{TMP} TMP fibre calculated thermal conductivity (0.57 W/m.K),
 K_{DIP} DIP fibre calculated thermal conductivity (0.24 W/m.K),
 $K_{Cellulose}$ Cellulose fibre calculated thermal conductivity (0.40 W/m.K),

χ_{TMP}	Fraction in volume of TMP in the blend (58%),
χ_{DIP}	Fraction in volume of DIP in the blend (14.5%),
$\chi_{Cellulose}$	Fraction in volume of cellulose in the blend (27.5%),
ε	Handsheet porosity (68%).

If we compare the calculated value with the measured one, the difference is about 0.002 W/m.K. So the models used seem to be well adapted. Nevertheless, some additional work is in progress to carry out measurements of thermal conductivity on handsheets made of different blends of pulps in various proportions.

THERMAL CONDUCTIVITY OF MODEL COATING LAYERS

To begin to understand heat transfer by conduction inside coated paper, it is of interest to study heat transfer through a coating layer. Indeed, when a conductive heat transfer occurs between a heating element and a coated paper, the heating element is first in contact with the coating layer.

Model coating layers made of talcum and lattice

In this study, we chose to study one coating pigment (talcum) and one kind of lattice (styrene butadiene). Coating colours were prepared at a solid content of $57 \pm 1\%$. Their pH value was adjusted with soda to 8.8 ± 0.2 . Coating colours were then degassed by flowing through a mesh.

One styrene-butadiene lattice was mixed, in variable amount, with four talcums, whose properties are given in Table 4.

We selected the talcums to obtain different mineral compositions and different particle sizes. The proportions of pigment and lattice are the following ones:

100 dry parts of pigment and 5, 10, 15, 20, 25, 30 and 50 dry parts of lattice.

Table 4 Properties of the four selected talcums.

	Talcum 1	Talcum 2	Talcum 3	Talcum 4
D50 (μm)	3.2	3.3	1.7	2.2
Composition	85% talcum 13% chlorite 2% dolomite	54% talcum 44% chlorite 2% dolomite	45% talcum 54% chlorite 1% dolomite	95–96% talcum 4–5% magnesite

Coating colours were metered on aluminium sheets, then dried. After that, the aluminium sheets were peeled off and we obtained what we called model coating layers.

We were unable to study pigment powders without lattice, because it was not possible to make films.

We measured the density of the model coating layers and we calculated their porosity (see Figure 6). We also measured their thermal conductivity – Figure 7.

On the Figure 6, we observe that the porosity of the model coating layer decreases sharply for lattice contents comprised between, 5 and 25. Then the porosity remains stable. Such an evolution has already been observed and explained by Lepoutre (4)

For the low lattice contents (inferior to 25 parts), the lattice fills in the void of the model coating layer as we increase its proportion. For higher lattice contents, normally, we should not have air anymore and when we add lattice, we should replace in proportion pigment by lattice. We notice that some air content is remaining in our model coating layers. Some microscopic observations of cross sections of the model coating layers showed that there were still air bubbles in the model coating layer despite our degassing. So we attribute the remaining porosity to air bubbles and not to a residual porosity due to the arrangement of the pigment lattice network.

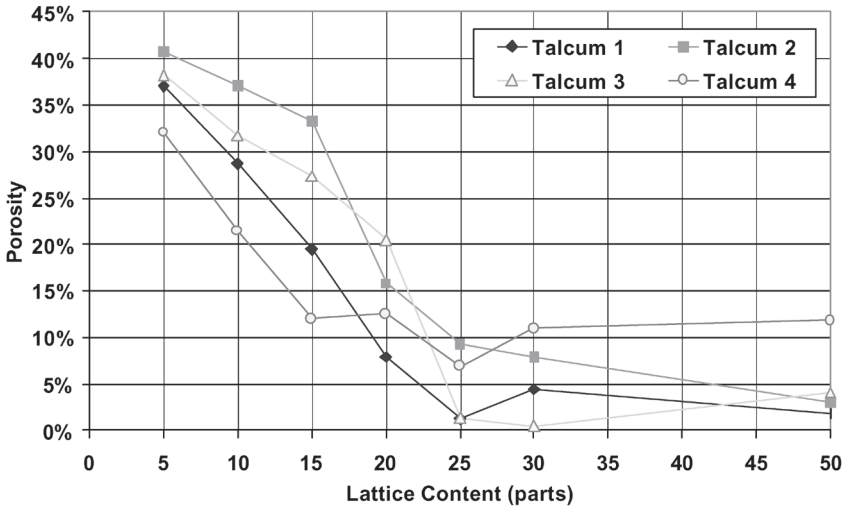


Figure 6 Porosity of model coating layers versus lattice content.

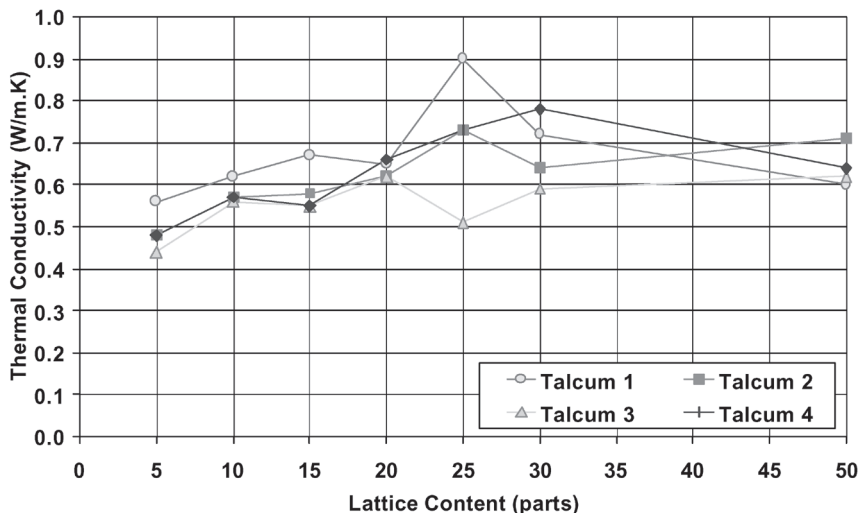


Figure 7 Thermal conductivity of model coating layers versus lattice content.

We measured the thermal conductivity of model coating layers (Figure 7).

The trends showed on Figure 7 can be explained by variations in composition and density. First of all, the thermal conductivity of model coating layers is two to three times higher than the thermal conductivity of handsheets. There are some differences between the curves, but it cannot be related to variation of the mineral composition of the pigments or to their particle sizes. Nevertheless, the four curves show the same trend: Between 5 and about 25 parts of lattice, the thermal conductivity of the model coating layers increases, then it decreases slightly.

This trend can be explained by the evolution of the composition of the model coating layer: In the first part of the curves, we observe coating layers made of pigment, lattice and air. As we increase the lattice content, we replace air, which is insulating, by lattice. So we filled in the voids in the pigment matrix by lattice. It is then quite normal that the thermal conductivity of model coating layers increases. For lattice content over 25 parts, the air content is stable and is due to air bubbles. So, as we increase the lattice content, we substitute some pigment in the matrix by lattice, which is less conductive. So, the thermal conductivity of the model coating layers decrease.

The constitutive models used previously with handsheets failed with

coating layers. It was not possible to calculate the thermal conductivity of a model coating layer from the values of conductivity of lattice and pigment and from the value of porosity.

Comparison between talcum, clay and calcium carbonate

In this study, we compared the thermal conductivity of model coating layers made of talcum, clay and calcium carbonate with the same lattice. The lattice content was in the usual range of the papermaking field (5, 10, 15, 20 and 25 parts in dry content for 100 parts of pigment). The clay was an English clay and the calcium carbonate was a ground calcium carbonate. We measured the thermal conductivity of these model coating layers (Figure 8).

The thermal conductivity of the model coating layers made from three different pigments increases with the lattice content (see Figure 8). The model coating layers made with clay and talcum have the same values of thermal conductivity, whereas the calcium carbonate leads to lower values. These results are very interesting, because, as these three pigments have almost the same values of density and heat capacity, it means that it is easier to heat (or to cool) a paper whose the coating layer contains talcum or clay than a paper whose coating layer contains calcium carbonate.

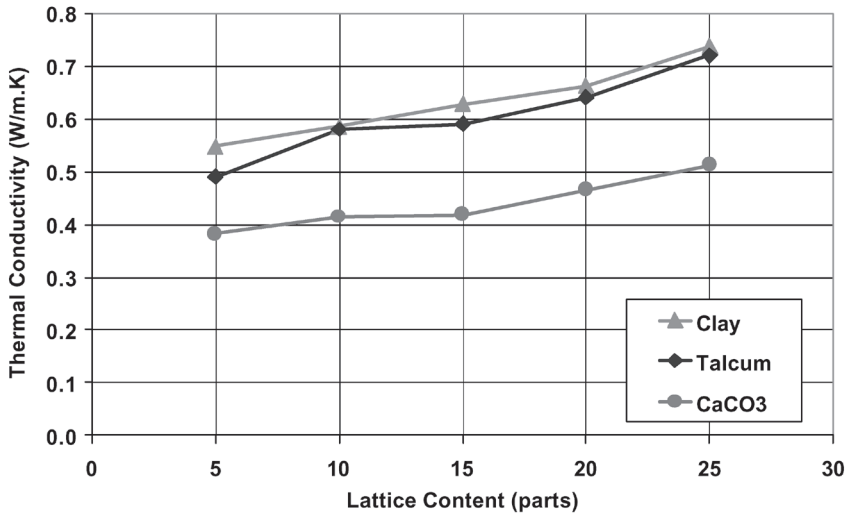


Figure 8 Thermal conductivity of model coating layers versus lattice content.

THERMAL CONDUCTIVITY OF AN UNCOATED BASE PAPER AND A LWC PAPER AT DIFFERENT CALENDERING LEVELS

Measurements on the papers

We measured the thermal conductivity of handsheets and of model coating layers. In this part we wanted to compare the thermal conductivity of an uncoated paper with the thermal conductivity of a coated paper.

For this, we selected a LWC paper for rotogravure printing and its uncoated base paper. Then, we supercalendered these papers in an increasing number of nips (varying between 1 and 9). The calender, we used for this trial, is described on Figure 9.

The calendering conditions were:

- Speed, 700 m/min,
- Temperature of the heated rolls 140°C,
- Linear load 180 kN/m.

We measured the thermal conductivity of the uncoated paper and the thermal conductivity of the LWC paper at different levels of calendering –

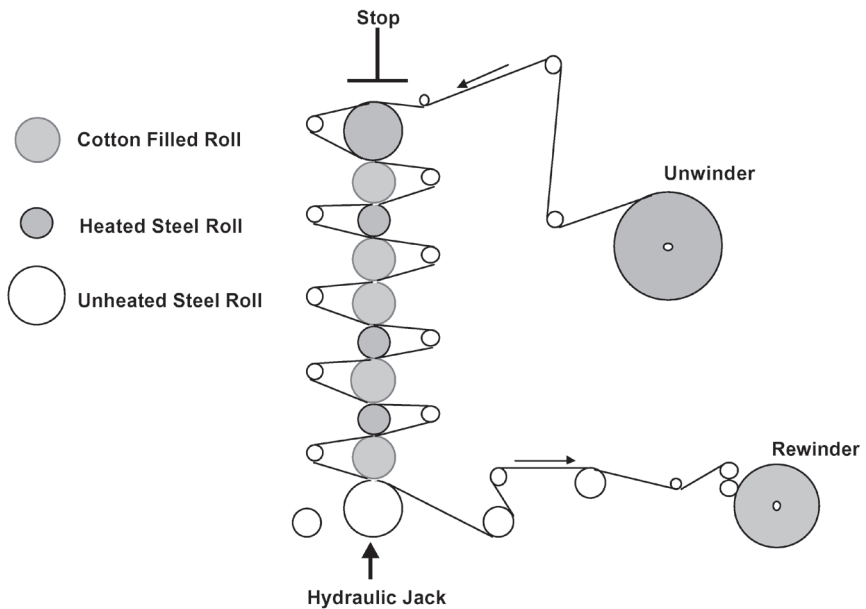


Figure 9 Diagram of the CTP's pilot supercalender.

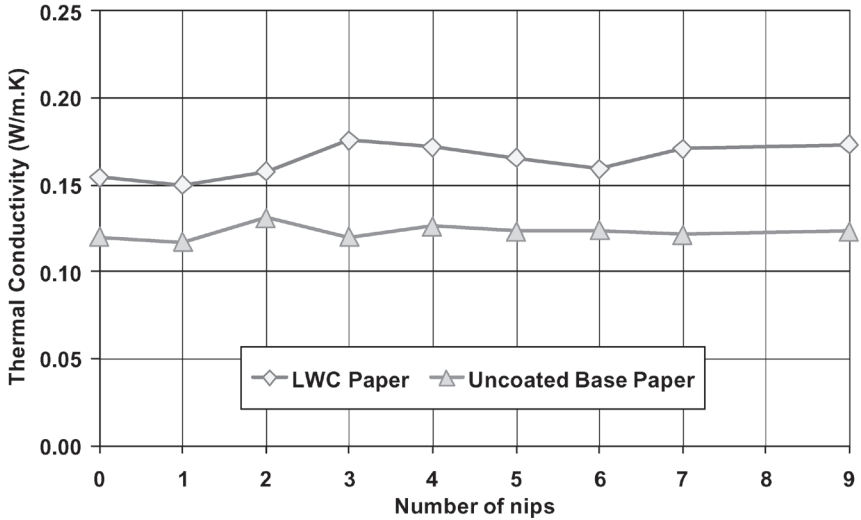


Figure 10 Thermal conductivity of a LWC paper and of its uncoated base paper versus calendering level.

Figure 10. The fibrous composition of the uncoated base paper is very close to the blend of pulp studied before. The coating colour is made with the lattice and the pigments studied previously (clay and talcum).

The uncoated base paper exhibited a lower thermal conductivity than the LWC paper, which is quite normal if we look at the results found on hand-sheets and on model coating layers.

Furthermore, the thermal conductivity of the LWC paper and the uncoated base paper show no variation when their thicknesses are reduced by calendering. This result has already been found by Morikawa [5] but is opposed to the results found by Kartovaara [6] and Niskanen [7].

We can imagine that the heat follows a certain path in the paper, and that the variations of thermal conductivity with the density depend on the way the density is modified (either by beating or by calendering) and depends perhaps also on the degradation that the fibres may experience during these treatments. Besides, the model structures we used to describe the thermal conductivity of paper don't take into account this path. It would be interesting to introduce the concept of solid phase tortuosity to take into account the fact that the path the heat follows is longer than the paper thickness.

Modelling of the thermal conductivity of coated papers

If we consider that the paper can be regarded as a three layer material (see diagram on the Figure 11), then from a thermal point of view, we can consider that three thermal resistances are disposed in series. We also assume that the two coating layers have the same composition and the same thermal conductivity.

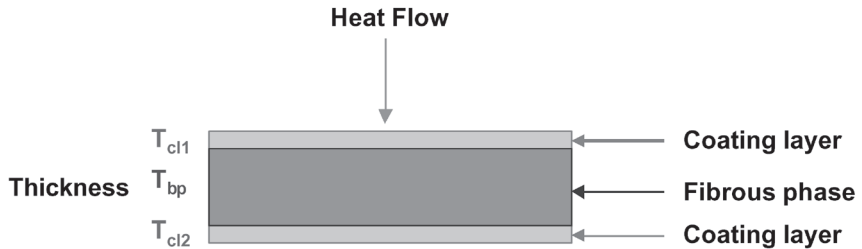


Figure 11 Diagram of a coated paper considered as a three-layer material.

Then the thermal conductivity of the coated paper should be calculated from the thermal conductivity of the uncoated base paper, the thermal conductivity of the coating layer, the thickness of the uncoated base paper and the thickness of the coating layers:

$$K_{\text{coated paper}} = \frac{T_{cp}}{\frac{T_{cl}}{K_{cl}} + \frac{T_{bp}}{K_{bp}}} \quad (10)$$

Where

- $K_{\text{coated paper}}$ is the thermal conductivity of the coated paper (W/m.K),
- K_{cl} is the thermal conductivity of the coating layers (W/m.K),
- K_{bp} is the thermal conductivity of the base paper (W/m.K),
- T_{cp} is the thickness of the coated paper (μm),
- T_{cl} is the total thickness of the coating layers (μm),
- T_{bp} is the thickness of the base paper (μm),

This calculation gives values of thermal conductivity for the coated paper, which are lower than the measured values. This result comes from the fact that we can't estimate correctly the thickness of the coating layers. Indeed, some pigments and lattice penetrate in the base paper when the paper is coated. Perhaps it would have been better to compare a single coated paper with the same paper coated another time to evaluate the availability of the multi-layer modelling.

CONCLUSION AND PROSPECTS

A very simple cost effective device for measuring thermal conductivity has been detailed. This device was validated with polymers and papers.

Thanks this device, we measured the thermal conductivity of handsheets made with different kind of pulps or blends of pulps. We used models to assess the thermal conductivity of the solid phase of papers; i.e. the thermal conductivity of the fibrous network. From this point, it seemed possible to calculate the thermal conductivity of a handsheet made from a blend of pulps knowing the porosity of the sheet, the fibrous composition and the thermal conductivity of each fibrous component. These assumptions have to be verified with other pulps and blends of pulps.

We carried out model coating layers and we measured their thermal conductivity with various compositions and with different natures, shapes, sizes, etc. of pigments. The model used previously with handsheet failed to calculate the thermal conductivity of the model coating layer from the composition and the porosity.

Thermal conductivity of a LWC paper and its uncoated base paper, calendered at different levels, showed only weak variations with thickness. To go further with the measurements, it would be interesting:

- to study the effect of the amount of fillers on the thermal conductivity of papers;
- to study a wider range of pulps and blends of pulps;
- to propose a constitutive model to calculate the thermal conductivity of model coating layers from the composition and the structure;
- to continue the study of thermal conductivity of papers with density.

So we have some values of thermal conductivity of base paper and coating layers. This step was necessary to calculate the penetration of heat in a coated paper during calendering or xerographic printing.

ACKNOWLEDGEMENTS

The authors would like to express their thanks to CSTB for the loan of the measuring probe, to P. Lafaverge and G. Eymin Petot Tourtollet (CTP) for the development of the measuring device and to L. Lyannaz for measurements.

We also like to express our thanks to Stora Enso Corbehem, Luzenac Europe, ECC International (Imerys now), Beloit Manhattan (Valmet now), and Rhodia (Latexia now) for their financial and technical support.

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Transcription of Discussion

THERMAL CONDUCTIVITY OF HANDSHEETS, PAPERS AND MODEL COATING LAYERS

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Editor's note – In the text of the paper 'lattice' is used as the plural of latex and should be spelt 'latice'

Dick Kerekes University of British Columbia

One of the factors that affects thermal conductivity of paper is moisture content it is very dependant on this. Applying a hot surface dries out the paper, or at least causes some moisture redistribution. Some of the techniques you cited, including my own in 1979, and going right back to Kirk's method, and I think some of the later techniques, attempted to overcome this by using transient-state methods which did not dry out the paper or affect its moisture content. In your method, I think you are using heating times of a couple of minutes (responding yes). Is drying a factor in your mind? Why did you not include it, or is it not important?

David Guérin

The measurements were done in conditioning room at 23°C and 50% moisture and the temperature of the paper is about 40–45°C, so there is an equilibrium in moisture, but in the samples of paper that we used it was difficult to measure the moisture content. We made measurements under different conditioning atmospheres. You can see the measurements concerning the base paper, and the light weight coated paper. We used three different atmospheres 30%, 50% and 70% relative humidity, so we didn't measure the

Discussion

moisture content of the paper, but we are sure that it varies according to these different atmospheres. You can see that in our range there was no variation of thermal conductivity according to the moisture content of the paper. I really think that it is due to our temperature of measurement being under 50°C, there is no evaporation in the paper.

Murray Douglas McGill University

I wasn't clear what pressure you used to make your measurement of thermal conductivity. Did you test various levels of pressure in your experimental equipment to see that measured thermal conductivities were independent of that pressure?

David Guérin

We carried out some trials concerning pressure. The pressure on the sample is about 100 kPa it is the same as in a classic μ meter thickness measurement, and we confirmed that there were no large variations of thickness of our samples. We also had a small weight on our thermal mass to measure the influence of an additional pressure on the thermal conductivity and we see no differences. I think that adding pressure will change the thermal contact resistance in a significant manner, but won't change the thermal conductivity of the paper. As you can see we have paper calendered at different levels and there is no variation of thermal conductivity, but there will be a great variation of thermal contact resistance of our paper.

Murray Douglas

Coming to your multi-nip predictions and measurements, for your predicted temperatures in the multi-nip case, how did you measure the length of the nip?

David Guérin

The length of the nip was measured with prints, and we compared these measurements with the Hertz-theory calculation. Of course it is a limitation of this modelling.

John Parker Consultant

With reference to Figure 3 in your paper two questions. Is the intercept a

function of the equipment, or is it a function of the material tested. That is, if you test different materials having very different conductivities and therefore giving lines of different slope do they all have a common intercept which would demonstrate that this was a function of the equipment? The second point I would like to make, is that I find it remarkable that you seem to find no contact resistance between separate sheets of paper. It is as if the roughness of a paper surface makes no contribution to contact resistance.

David Guérin

I will answer the second question first about the contact resistance. As soon as there is a contact between two materials, then there is a contact resistance as you can see here (Figure 5) between the heating plate and the sample sheet and between the thermal mass. There is also contact resistance between the different samples, and with our device we measure the total resistance and so we can read out measurements using a stack of 1–6 sheets having the same thickness, or using one sheet having a varying thickness and the few differences that you can observe between the yellow and the green squares means that there is no contact resistance between the samples. There is only a contact resistance between the heating element and the sample and that is what we measure and perhaps when you use a pile of papers it is sufficiently deformable to have a rather good contact in terms of heat conduction between the different samples. With regard to the first question, the contact resistance differences will depend on the pressure, and on the nature of the thermal element, for example in the calender where you have a soft roll, the contact resistance won't be the same as the contact resistance with a steel roll.

Gary Baum Institute of Paper Science & Technology

Did you change the thermal mass or the pressure at all?

David Guérin

It was always the same pressure, but some authors have shown that there is no contact resistance for pressures over 12 MPa.