Assessment of Physical Properties

of

Spacer Fabric

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Abstract

At the Saxion University of Applied Sciences there is a department that initiates projects in co-operation with the business sector and the Twente University. In 2014 a project was initiated with the intention to start using spacer knittings in the building industry. However, it was unknown what the thermal properties of spacer knittings are and what variables can be of influence on these properties.

For measuring thermal conduction there are various methods available. For this study a measuring method in conformity with ISO 8990 was chosen. The measurement set-up was specifically built and implemented for this study.

The various kinds of spacer knittings were made on a circular weft knitting machine. The 8 spacer knittings differ from each other in terms of stitch size, yarn type and thickness.

It turned out that the thermal resistance is low, so that an application as insulating material is unfit. As a cause that this thermal resistance is low it can be assumed that the airflows through the spacer knitting conduct the heat. After studying the measuring results and theoretical models a possible relationship has eventually been found between the different parameters. Further research is needed to determine whether this relationship between stitch density, thickness of the spacer knittings and the yarn type used for the knitting, can be widely applied.

The developed measurement set-up has the advantage that one side of the material to be tested is accessible. This offers the possibility to be able to start investigating airflows through the knitting.

Declaration

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Last but not least, a special thanks to my family, who has supported me over the years.

Enschede, September 2015

1. Introduction

1.1 The development of living facades made of 3D fabrics

In January of 2014 the project Responsive Textile Facades was starting. The hypothesis was that 3D knitting are versatile materials that are considered to be starting materials for responsive textile facades. (EuropeanUnion, 2013)

Figure 1 Curtain wall house (www.Ivao.co, retrieved 12 November 2014)

This project is part of the EC work programme: adaptable envelopes integrated in building refurbishment projects. (Figure 1) The objective of the project is to address the social and demographic developments by creating dynamic sustainable, flexible and temporary construction applications based on textile technology. The need for temporary structures is currently already clear. (TNOResearch, 2006)

The idea is to develop intelligent and dynamic plug and play solutions that later can simply move to other properties such as a temporary incorporation into 70s facades. These building elements are fitted with the obvious technical functionality, but in addition must be made smart in the sense that they react dynamically to stimuli from the environment, like ventilation and light.

One of the latest developments in textile technology are 3D fabrics. At this moment these fabrics are used in textile constructions like beds and seats. Important properties of these fabrics are breathability, insulation and transport of moisture. It is likely that there is also the possibility to give these fabrics supplementary properties, like sensors and LEDs, which give the fabric SMART like properties.

The expectation is that there are many advantages for the application of a knitted textile construction. It is necessary to know which properties are important for application in building constructions. Important for application is that the required properties are predictable, so that these properties link with the performance demanded in building projects.

1.2 Objective

To enable decision-making about the applicability of textile materials in building and construction, the physical properties will be included in a test model.

The aim of this research is to measure the influence of variables like raw material and thickness on the physical properties of a spacer fabric with a simple developed measuring instrument.

For the development and practical testing of this model it is important to study the following subjects:

- Textile materials;
- Spacer knitting;
- Heat transfer;

- Methods for Testing textile;
- Methods for testing thermal conductivity.

1.3 Thesis layout

In the introduction it is pointed out that for developing a test model, it is important to first study the theoretical background of knitting and thermodynamics. The result of the investigation into knitting and its possibilities is described in chapter 2. It was investigated how spacer knittings can be made with weft or warp knitting.

The result of an investigation into heat transfer: radiation, conduction and convection is described in chapter 3. How theoretically heat transfer could take place in spacer knittings is examined here in more detail.

In order to be able to eventually measure heat transfer in spacer knittings, a literature study has been conducted on possible measuring methods for heat transfer and the possible temperature sensors needed for it.

Ultimately the practical experiment is described in chapter 5. Firstly, choices need to be made, such as what type of spacer knitting and what measuring method for heat transfer and temperature measurements should be selected. This chapter describes how the self-constructed measuring set-up for heat transfer should be built. What spacer knitting can be made on what kind of knitting machine is examined in further detail. Finally a description can be given as to how the test should be carried out.

This leads to a number of test results that are elaborated in chapter 6. Here one can find the calculations that should give the answer to the main question, namely what factors affect the heat resistance in spacer knittings? The conclusions of the results in chapter 6 are described in chapter 7, possible recommendations are made in chapter 8. The results of the measurements are specified in the relevant annexes.

2. Literature review: knitting technology

2.1.1 Introduction weft and warp knitting

Knitting is a technique in which the connection of the textile construction is obtained by interlocking loops, formed from a single yarn or from many. (Eberle, 2005) Some characteristic properties are:

- the construction is stretchy;
- the product is breathable;
- the structure is voluminous;
- if one thread breaks, the connection in the construction is broken.

In the knitting industry, there is a distinction between warp and weft knitting. In weft knitting, one thread is lead to all needles that each forms the loop. (Figure 2 Weft knitting (University of Manchester, MATS 66561, 2013) The threads run in the width direction of the knitted fabric.

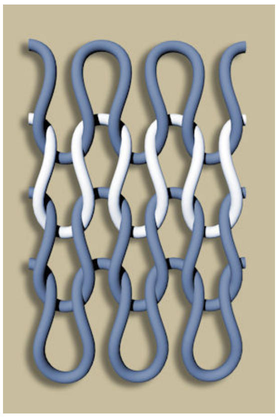

Figure 2 Weft knitting (University of Manchester, MATS 66561, 2013)

In warp knitting, every needle has its own thread. (Figure 3) The threads run in the linear direction of the knitted fabric.

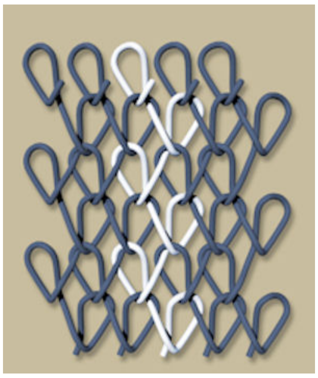

Figure 3 Warp knitting (University of Manchester, MATS 66561, 2013)

Having several stitches on top of each other is called a wale and having several stitches beside each other is called a course. A wale runs vertically and is produced by the same needle on successive knitting cycles. (Figure 4) A course runs horizontally and is produced by adjacent needles during the same knitting cycle. The number of wales and courses is an important quality feature of a knitted fabric.

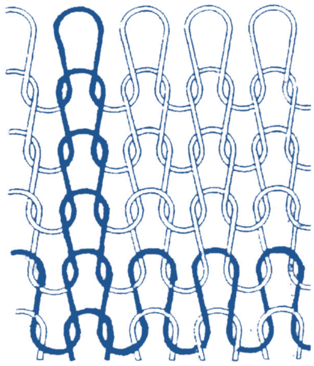

Figure 4 Courses and wales (Zwiers, 1998)

2.1.2 Weft knitting basic structures

There are 4 primary base structures in weft knitting (Spencer, 2010) from which all weft knitted fabrics and garments are derived:

- Right-left knit fabric
- Left-left knit fabric
- Right-right knit fabric
- Interlock

An RL knit fabric (Figure 5) is a knitted fabric that consists of right stitches at the front side (technical front) and of left stitches at the back-side (technical back). Properties are: strong tendency to curl, stretchy but little elasticity.

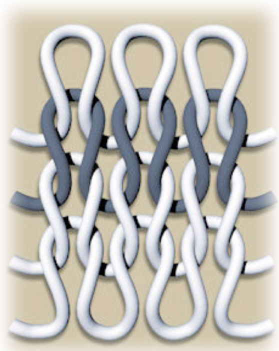

Figure 5 RL knit fabric (University of Manchester, MATS 66561, 2013)

In an RR knit fabric, (Figure 6) only the right stitches are visible on the front and back-side. The tensions that are formed in the knitted fabric cause the wales to be pulled towards each other. Because of this, the left stitches are covered by the right stitches. In reality, the knitted fabric consists of alternating left and right wales. Important properties are: no tendency to curl, very stretchy and elasticity in the width direction.

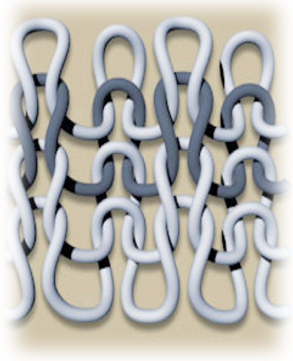

Figure 6 RR knit fabric (University of Manchester, MATS 66561, 2013)

An LL knit fabric (Figure 7) consists of alternating right and left stitch courses. The tensions that are formed this way cause only the left stitches to be visible. Properties of this type of knit fabric are: no tendency to curl, very stretchy and elasticity in the linear direction

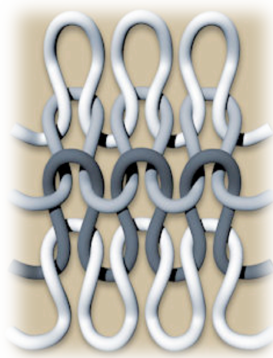

Figure 7 LL knit structure (University of Manchester, MATS 66561, 2013)

The final basic construction is the interlock. (Figure 8) In this fabric, two RR knit fabrics are knitted through each other. Properties of an interlock knitting fabric are: flat-lying knit fabric, very limited stretch and elasticity in the linear and width direction.

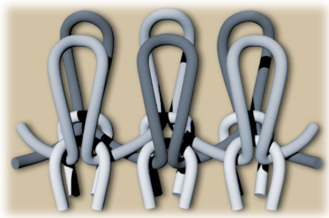

Figure 8 Interlock (University of Manchester, MATS 66561, 2013)

The basic constructions can be directly related to the type of machine they can be created on. A knitting machine consists of 1 or 2 needle beds that can be designed in either a straight line or circular design. These are called flat knitting machines and circular knitting machines. The principle of flat or circular knitting is the same. A needle bed is a steel plate in which grooves have been milled. (Figure 9)

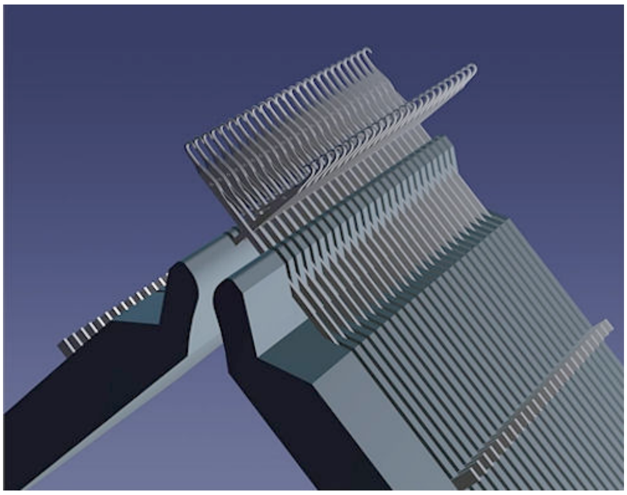

Figure 9 Front and rear needle bed with needles (University of Manchester, MATS 66561, 2013)

The knitting needles can move up and down in these grooves. The needles are fitted with a butt, (Figure 10) which makes it possible to operate these. The upper part of the needle consists of a head and a movable latch.

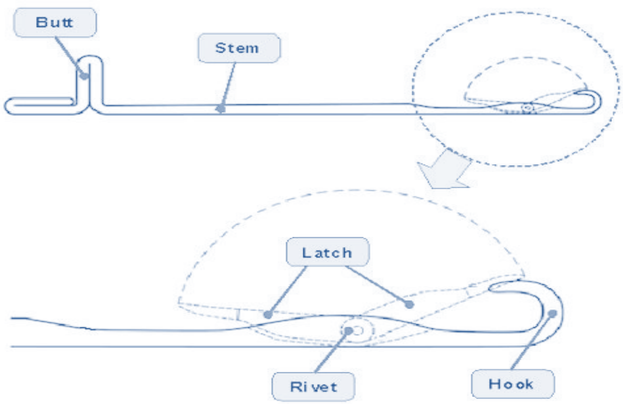

Figure 10 Latch needle (University of Manchester, MATS 66561, 2013)

If the needle is brought into the upper position, yarn can be placed in the head. The moment that the needle moves down again, the old stitch that was located on the stem will close the spoon and gets thrown off over the needle. The new stitch is located in the head of the needle. If the needle is not moved upwards, a floating yarn is created. A needle can also be moved upwards in half position. The old stitch is not thrown off, but remains on the spoon if the needle is in half position. This is called a tuck. By using these three needle positions and the four primary base weft knitted structures, all possible types of knitting can be created.

2.1.3 Warp knitting basic structures

In warp knitting, every needle has its own thread. This means that there have to be as many threads as needles. These threads are wound on a warp beam, just as with a loom. The threads are simultaneously fed to all needles with a guide bar. The variations in the movements the guide bar makes in relation to the needles (Figure 11) determine the structure. (Spencer, 2010)

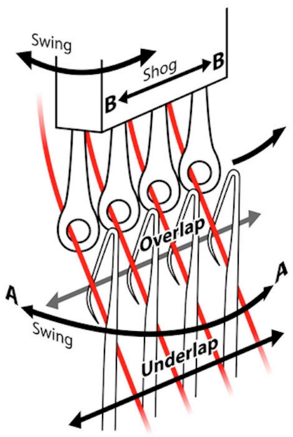

Figure 11 Guide bar movements (University of Manchester, MATS 66561, 2013)

There are 5 variations:

- an overlap, followed by an underlap in opposite direction (closed stitch);

- an overlap, followed by an underlap in the same direction (open stitch);
- only overlaps, and no underlaps (open laps)
- only underlaps and no overlaps (laying-in)
- no underlaps and no overlaps (miss-lapping)

Just like with weft knitting, warp knitting machines can be designed with 1 or 2 needle beds. By using several eye-pointed needle bars with their own controls, a combination of structures can be made. This often results in dimension-stable knit fabrics in both length and width direction.

In warp knitting machines, we distinguish between Raschel and tricot warp knitting machines. Tricot warp knitting machines are equipped with sinkers, which are necessary for the stitch formation. (Figure 12) The operation strongly resembles the principle of stitch formation in an RL weft knitting machine. The fabric is transported at an angle of approximately 90° in relation to the needles. The speed of this type of machine is high, and the number of eye-pointed needle bars is usually limited to 4.

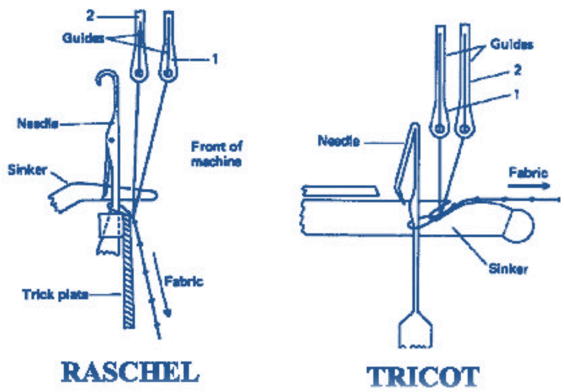

Figure 12 Difference between Raschel and Tricot machine (Spencer, 2010)

The Raschel warp knitting machines do not have this type of sinkers. The stitch formation takes place by means of a trick plate. (Figure 12) The fabric that is created is transported at an angle of 180⁰ in relation to the needles. The take-down tension on this fabric immediately prevents the old stitch from coming upwards with the needle movement. This makes this type of machine suitable for making gaps in the knitted fabric. The number of eye-pointed needle bars is high (up to 70), and the speed is more limited compared to the tricot warp knitting machines.

2.2 Spacer fabric

2.2.1 Weft or warp

Spacer fabrics can be found in many different designs. An important reason for these differences is whether the spacer fabric is a warp or a weft knitted fabric. In addition, there are various pattern possibilities and variations in the material composition. Also, the yarn thickness and the coarseness (division) have an important influence on the final properties. First of all, we will look at the most important distinction for spacer fabrics, i.e. which knitting technique has been used: warp or weft knitting.

2.2.2 Weft knitted spacer fabric

A weft knitted spacer fabric consists of two RL knittings, which are connected to each other by tuck stitches. In Figure 13 the knitting scheme for a spacer fabric is drawn.

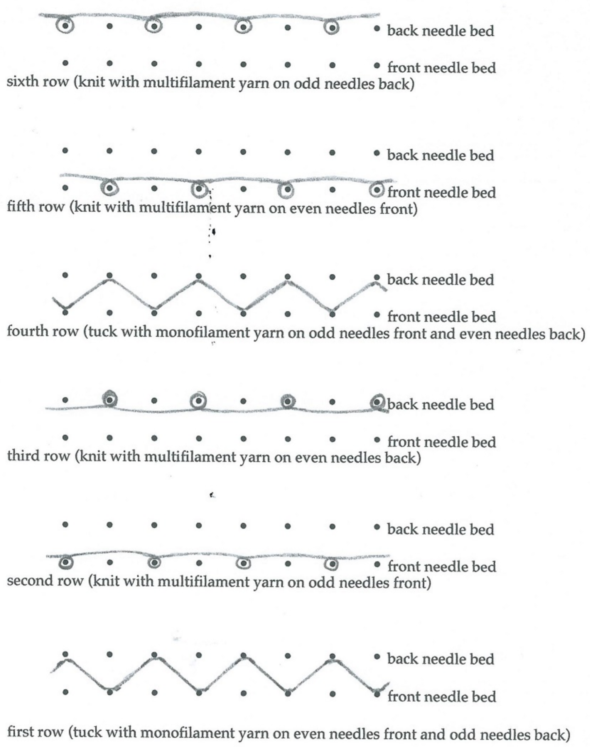

Figure 13 Knitting scheme spacer fabric weft knitting

A spacer fabric can only be knitted on a machine on which at least two levels of needles can be selected. This has to do with the tuck stitch that needs to be able to be made. If one needle bed was tucked simultaneously on all needles, and after that, all needles of the same needle bed were knitted, the tuck stitches would come loose from the needles. That is why it needs to be tucked and knitted in turns. Often these types of knitted fabrics are knitted on an interlock machine or a knitting machine with electronic needle operation. A spacer fabric can be made on a flat knitting machine or a circular knitting machine. The thickness of the spacer fabric is determined by the spacer between the two needle beds. On a flat knitting machine, the spacer between the needle beds cannot be varied due to the construction of this type of machine. Therefore, it is not possible to vary the thickness of a spacer fabric on a flat knitting machine. On a circular knitting machine, the dial can be adjusted in height. This means that the spacer between the needle beds is variable, and therefore the spacer between the two RL knit fabrics is also variable. In other words, the thickness of the spacer fabric is adjustable on a circular knitting machine. The extent to which this is adjustable is limited, however. In a standard (interlock) circular knitting machine, the yarn carriers are mounted on the dial cam plates. (Figure 14) Once the dial is placed in a higher position, the yarn inlay for the cylinder needles will also be higher. If the dial is placed too high, it will not be able to have the yarn placed into the cylinder needles. This is the limitation for the height adjustment, and with that also the limitation of the adjustment of the thickness of the spacer fabric.

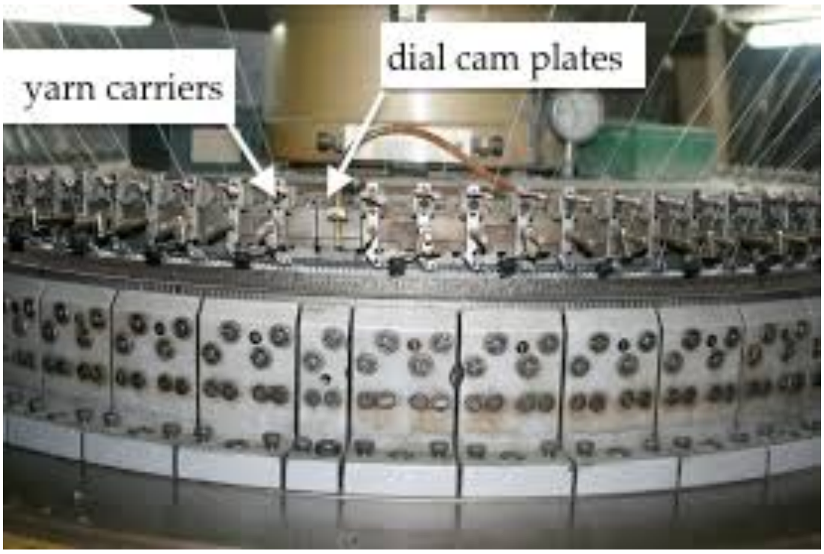

Figure 14 Yarn carriers mounted on the dial

A weft knitted spacer fabric is built up by alternately knitting a stitch course on the cylinder needles, the rib needles, and the tuck stitch on both needle beds. This means knitting with three yarn systems. This offers the possibility of applying different materials and or yarns. To make sure that both RL knitted fabrics are kept at a spacer, the yarn for the tuck stitch, which connects both fabrics to each other, needs to have enough stiffness. That is why for the tuck stitch, monofilament yarn is often applied. (Figure 15)

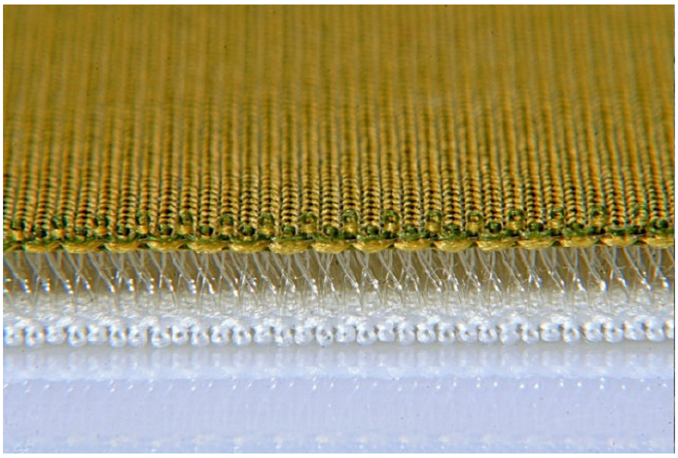

Figure 15 cross section spacer knitting (www.cetriko.com, retrieved 16 January 2015)

The two RL knitted fabrics that are formed by the dial and cylinder needles can be made from different material. It would be possible for example to make a spacer fabric with cotton on the one side and polyester on the other side.

On a circular knitting machine, a yarn can be inlayed at the place where the tuck stitch is created. This gives the possibility to fill up the spacer fabric with a material that can give specific properties to the spacer fabric.

Because an RL knitted fabric is applied on both sides, a fabric is created with elasticity in length and width. The gauge and the stitch size influence this as well. The gauge and stitch size are closely related to the thickness of the yarn. Directly connected to this are the properties of weight per square meter and the tensile strength.

2.2.3 Warp knitted spacer fabric

In chapter 2.1.3 it is noted that because of the construction of Raschel warp knitting machine, there is an option to make gaps in the fabric, which is difficult on a tricot warp machine. Spacer warp fabrics are therefore often knitted on a Raschel warp-knitting machine.

The Raschel (Raz, 1987) flat knitting machine, contrary to the weft flat knitting machine, has the option to vary the spacer between the needle beds. Every needle bed has its own guide bar. This makes it possible to adjust the spacer between the needle beds much more than in a weft circular knitting machine. Spacer fabrics that need to have a larger spacer (thickness) are therefore made as warp knitted fabrics. The knitting scheme for a spacer fabric with gaps is drawn in Figure 16. The gaps in the fabric are created due to a combination of various knitting and a partially threaded eye-pointed needle bar.

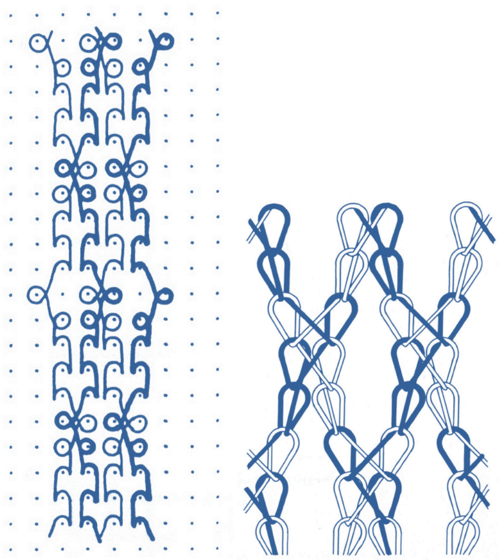

Figure 16 Scheme for making gaps with warp knitting (Raz, 1987)

The monofilament yarn between the layers is knitted as a tuck stitch into the two layers. The possibilities with variations in yarn thicknesses and types of yarn are identical to weft knitting.

To give a warp knitted fabric stability, two or more knitting structures are applied. By example a Locknit is a construction built up with a closed 2 and 1 and a closed tricot with counter lapping. Because of the counter lapping the underlaps are in the opposite direction. Therefore, the elasticity of a warp fabric is significantly lower than a weft fabric.

2.3 Fabric geometry: weft knitting

2.3.1 Introduction

For the ultimate calculation model, a number of variables needs to be known. These variables are determined by a number of specific parameters of the knitted fabric. The most important parameters are:

- Type of yarn
- Yarn thickness
- Knitting construction
- Size of stitch

The variables for the calculation model need to be determined from these data. One of the most important variables is the surface of the knitted fabric. The surface of the knitted fabric consists of the stitches and open gaps in between. It is of utmost importance to know how large this surface area is, and how large the in-between gaps are. Determining factors for this are the yarn thickness and the stitch size. Also, the construction of course plays an important role; this determines how much yarn is located at the surface are.

Various models have been developed to estimate / calculate the stitch size in relation to the yarns. A division by type of calculation is:

- Geometric model
- Geometric-mechanic model
- Energy model
- Micro-particle model

The geometric model is most successfully applicable to more complex knitting constructions. Therefore the geometric model will be applied for this research project.

2.3.2 Plain weft knitted fabrics according to Peirce

The first concepts for knitting geometrics assumed that the shape of a knitting stitch can be represented by arcs of a circle (Peirce, 1947). Pierce assumed that the stitches touch each other at the intersections (Figure 17) as to have maximum cover. In addition, it was assumed that the axis of the yarn in every stitch course is located on a cylinder, with such a curve that the intersections leave enough room for the yarns.

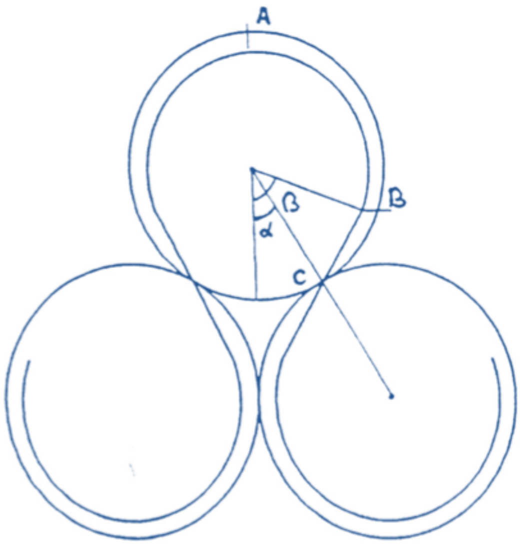

Figure 17 Pierce: knitting geometric by arcs of a circle

Starting from these assumptions, Pierce had calculated the yarn length of the stitch in the following way:

l = yarn length of the stitch

d = diameter of the yarn, so d=2r (radius of the circle)

$$l / 4 = 3d(\pi-\beta)+2d\sin(\beta-\alpha) \qquad (2.1)$$

α=30°=0.5236 rad

$\cos(\beta-\alpha)=1.5/2 \rightarrow \sin(\beta-\alpha)=\sqrt{(1-0.75^2)}=0.6614$ (2.2)

$\beta-\alpha=41°25' \rightarrow \beta=71°25'$

$l/4d=2.8428+1.3229=4.1657$

$l/d=16.6628$ (2.3)

In this calculation, the yarn that lies in the area of the knitting as well as in the area perpendicular to this in curves is not taken into account.

2.3.3 Plain weft knitted fabrics according to Munden

Munden (Munden, 1959) assumed a knitting stitch as a three dimensional construction. The yarn is curved in the area of the knitting as well as in the area perpendicular to this.

Assuming that the relaxed size of the knitted fabric is determined by the shape of the knitting stitch that belongs to the state of minimum energy. Furthermore, it is assumed that this shape is a geometrical property of the knitting stitch, and is independent from the physical properties of the yarn or the amount of yarn per stitch.

This assumption is based on the work of Leaf. Leaf (Leaf, 1955) has calculated that the shape of a homogeneous strip, that is bent until the tips lie parallel to each other and touch each other, is independent from its physical properties: the thickness and length of the material. A precondition of the above is that the material is not plastically deformed during the creation.

Munden assumed a knitted fabric in a completely relaxed state. In Figure 18 two identical in-shape (half) knitting stitches are drawn: AB and A'B'.

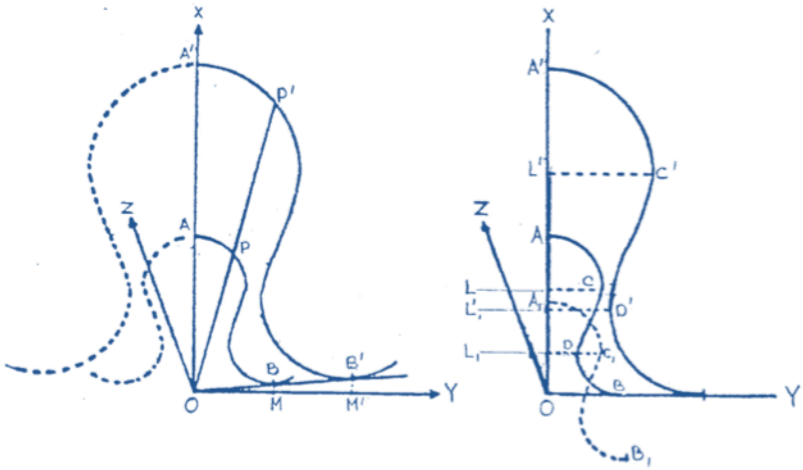

Figure 18 Knitting geometric of Munden

The vector OP will cut the stitch AB in P and the stitch A'B' in P', so that the following applies:

$OP'/OP = p$

The following likewise applies to the stitch lengths:

$l' / l = p$

The following applies for the position of vector OP in the surface OZY perpendicular to the surface of the knitted fabric:

$OB' / OB = p$

The projections of B and B' on OY are M and M'. Because of the similar triangles, the following applies:

$OM' / OM = p$

OM is half the spacer between the wales from the stitch AB and OM' is half the spacer between the wales of the stitch A'B'. The following then applies:

Number of wales APB per cm / number of wales A'P'B' per cm = p

For a similar connection for the number of courses per cm, it is necessary to look at both the shape of the stitch, as the location where the stitches hang into each other.

In Figure 18 the largest width of the stitch is indicated with C and C′, the smallest width is indicated with D and D′. Projection of these points on the Y-axis: L and L′. The stitch $A_1C_1B_1$ of the following course is equal in size and shape to ACB and drawn in the position in which both stitches are intertwined. The following then applies:

$AL = A_1L_1$, and therefore also $AA_1 = LL_1$.

The spacer between the stitch courses equals LL_1. A′C′D′ equals ACD. Therefore, the following applies:

$OL'_1 / OL_1 = p$

and

$OL' / OL = p$

so:

$(OL' - OL'_1) / (OL - OL_1) = p = L'_1L' / L_1L$

p= courses per cm A′C′B′ / courses per cm ACB

p= l′ / l

courses per cm = K_r / l (2.4)

K_r= constant

For the number of wales, the same can be formulated:

wales per cm = K_s/ l (2.5)

K_s= constant

For the stitch density (N), the following then applies: wales per cm x stitches per cm

$N = K_d / l^2$ (2.6)

K_d= constant

$K_d = K_r \times K_s$ (2.7)

2.3.4. Cover Factor

Munden has introduced a cover factor, just like what is being used at weaving, to indicate the relative density of a knitted fabric. In the course of time, this name has changed into the tightness factor (TF). The TF indicates the proportion of the surface of the stitch that is taken up by the yarn with the entire surface.

It is assumed that the yarn has a circular diameter, and the fabric is two-dimensional. In that case, for the surface occupied by the yarn, per cm^2, the following applies:

$A = N \times l \times d$

According to Munden (2.6) the following applies: $N = K_d / l^2$

Therefore: $A = (K_d \times l \times d) / l^2$ (2.8)

For practical purpose the cover factor can be defined as: $\sqrt{Tex} / l$. (Au, 2011)

2.4 Fabric geometry: warp knitting

2.4.1 plain warp knitted fabrics

For warp knitting there is also a geometric model. The aim was to calculate the run-in for the knitting machine. G.L. Allison started (Raz, 1987) with a geometric model, he split the stitch in 4 parts. (Figure 19) First the head like a circle with a radius of 2d. Then two arms as a straight line and last the underlap.

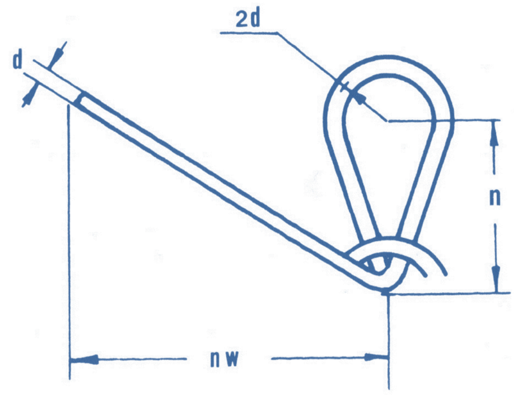

Figure 19 Warp knitting stitch (Raz, 1987)

Diameter of the yarn: d

Course spacing: c (1/CPC)

Wale spacing: w (1/WPC)

Underlap in needle spacing: n

The total yarn length can be calculated as follow:

Head: $\pi \times 2d$

Arms: $2\sqrt{(4d^2 + c^2)}$

Underlap: $\sqrt{(c^2 + n^2w^2)}$

Correction for the yarn passing the loop's base: $2 \times d$

The total loop length will be the sum of the above parts:

$$l = \sqrt{(c^2 + n^2w^2)} + (\pi \times 2d) + 2\sqrt{(4d^2 + c^2)} + (2 \times d) \quad (2.8)$$

This model is very simple and gives fairly results.

Most of the time they use synthetic yarns. These fabrics must be heat set for fixation of the dimensions. Therefor it is not possible to assume of a fabric in a relaxing state. Raz calculated in this case the length of yarn in one stitch. He developed a new model:

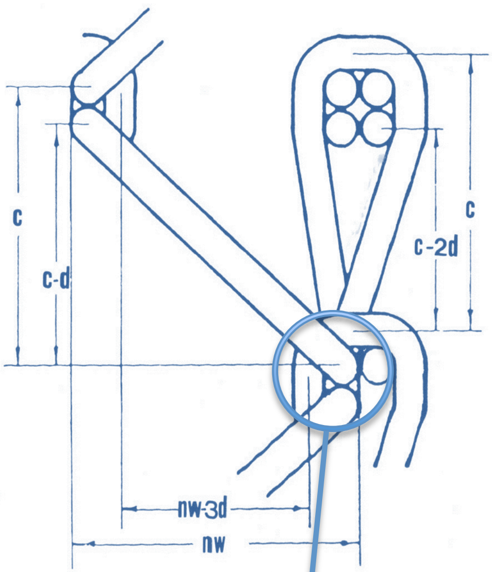

Figure 20 Warp knitting loop model (Raz, 1987)

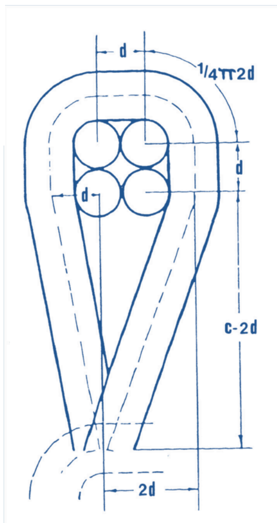

Figure 21 Part of the loop model (Raz, 1987)

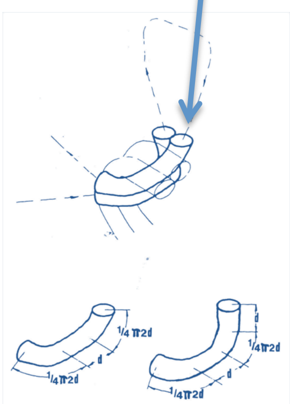

Figure 22 Yarn root configuration (Raz, 1987)

Underlap (Figure 20): $\sqrt{(c-d)^2 + (nw - 3d)^2}$ (Pythagorean theorem) (2.9)

Loop's head (Figure 21): $3d + 2(\frac{1}{4}\pi 2d)$ (2.10)

Loop’s arm (Figure 21left): $\sqrt{(c-2d)^2 + d^2}$ (2.11)

Loop’s arm (Figure 21right): $\sqrt{(c-2d)^2 + (2d)^2}$ (2.12)

Yarn root of the loop (Figure 22): $2\pi d + 3d$ (2.13)

Total loop length (2.9 + 2.10 + 2.11 + 2.12 + 2.13):

$$l = \sqrt{(c-d)^2 + (nw - 3d)^2} + \sqrt{(c-2d)^2 + d^2} + \sqrt{(c-2d)^2 + (2d)^2} + 3d(2+\pi) \quad (2.14)$$

Research (Raz, 1987) proved that the linear deviation between the calculated run-in and the course spacing was about 2 %. The relation between the run-in and course spacing for front and back guide bar is in Appendix 1.

3. Literature review: heat transfer

3.1 Introduction

Heat transfer can take place in three ways. (Giancoli, 2014) (Cengel, 2011) These are: radiation, conduction or convection. Heat transfer can also occur in a combination of those three ways. In radiation, the heat transfer takes place by way of electromagnetic waves. Contrary to conductivity and convection, no carrier is needed. In heat conductivity, the heat transfer takes place by the (more fiercely) vibrating molecules. The material will not change its position. With convection however, the carrier changes its position, which therefore can basically only take place with liquids or gases. The driving force is always a difference in temperature.

3.2 radiation

In radiation, the heat transfer takes place by way of electromagnetic waves. These electromagnetic waves are located as recommended by The International Commission on Illumination in the area between 0.7 to 1000 μm. (Figure 23) This is the infrared radiation zone. Every object is capable of radiating heat or absorbing heat.

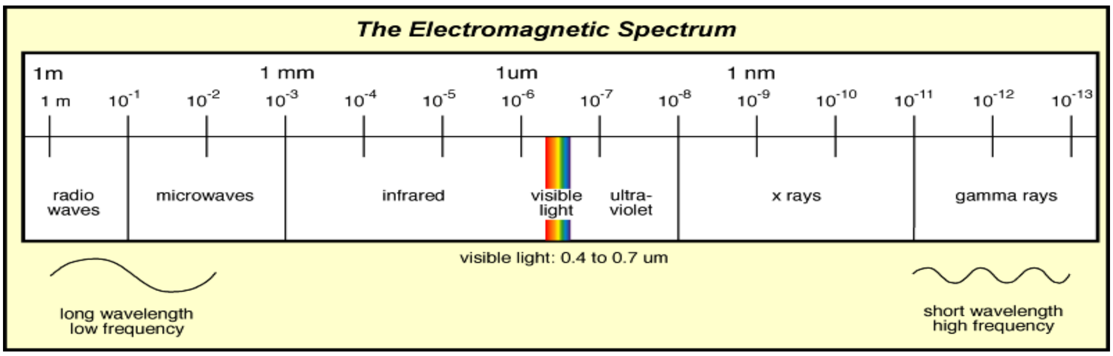

Figure 23 Electromagnetic spectrum (www.columbia.edu, retrieved 26 April 2015)

The energy flow that leaves an object is called emittance. (M) This increases with the object's temperature, and it depends on the material and the condition of the surface. The material and the condition of the surface are indicated by the emission factor (ε). In Table 1, the emission factor of several materials is presented.

Table 1 Emission factor (Giancoli, 2014)

Material	Emission factor (ε)
Aluminium polished	0.08
Aluminium oxidised	0.40
Chrome	0.058
Wood	0.94
Ice	0.97
Glass	0.94
Paper	0.97
Cotton	0.77
Copper polished	0.03
Copper oxidised	0.76
Cork	0.70
PE	0.94
PP	0.94
Pes	0.94
PVC	0.94
Paint black	0.97
Paint white	0.95
Rubber	0.94

The heat transfer per square meter of an object warmer than 0 K is indicated by the heat flux density. The formula is:

$$M = \varepsilon \cdot \sigma \cdot T^4 \quad (3.1)$$

The symbols mean:

M = emittance [W/m^2]

ε = emission factor ($0 < \varepsilon < 1$) [-]

σ = Stefan–Boltzmann constant [5,67.10^{-8} W/m^{2}K^4]

T = temperature of the surface [K]

The amount of radiation energy an object receives is called irradiance (E). Part of the radiation can be absorbed by the surface, another part is reflected and the rest can pass through. The extent to which a body (partially) absorbs, (partially) reflects, or (partially) lets through heat, depends on the material, the temperature and the condition of the surface.

The fraction of radiation that is absorbed by a body is called the absorption factor (α), the fraction of radiation that is reflected is called the reflection factor (ϱ) and the fraction that is permeated is called the transmittance factor (τ). This formula applies:

$$\alpha + \varrho + \tau = 1 \quad (3.2)$$

A surface with temperature T_1 will therefore lose energy by emission of radiation ($\varepsilon \cdot \sigma \cdot T_1^4$) and gain energy by absorption. ($\alpha \cdot E$)

Suppose that the heat being received is originating from a black radiator with the same temperature as the object, the following applies:

$$E = \sigma \cdot T_0^4 \quad (3.3)$$

In that case, the net heat loss per m^2 by radiation is:

$$M - \alpha \cdot E \quad (3.4)$$

Therefore, the following formula applies: $(\varepsilon \cdot \sigma \cdot T_1^4) - (\alpha \cdot \sigma \cdot T_0^4)$ (3.5)

In thermal equilibrium state, the absorptivity of a body equals its emissivity.

In other words:

In a steady state the amount of heat Q_r that is radiated by an object therefore depends on:

The surface: A [m^2]

The emission factor: ε [-]

The temperature of the object: T_1 [K]

The temperature of the environment: T_0 [K]

In that case, the following formula applies:

$$Q_r = \varepsilon \cdot \sigma \cdot A \cdot (T_1^4 - T_0^4) \quad \text{[J/s] or [W]} \quad (3.6)$$

3.3 conduction

In heat conduction, the heat transfer takes place by the kinetic energy of the molecules in the matter itself. The heat transferring particles do not change position. Contrary to radiation, a transferring medium is required. The driving force is temperature difference. The extent to which heat is transferred depends on the surface, the spacer (thickness), and the thermal conductivity of the material. In a formula:

$$Q_w = (A \cdot (T_1 - T_2)) \ / \ (d \ / \ \lambda) \quad (3.7)$$

The symbols mean:

Q_w = amount of heat that is conducted [J/s] or [W]

A = surface area of the material [m^2]

T_1 = temperature one side of the material [K]

T_2 = temperature other side of material [K]

d = thickness of the conductive material [m]

λ = thermal conductivity of the material [W/(m.K)]

In case there are several layers on top of each other, the heat flow will encounter resistance in each of these layers. In that case, the thickness and the corresponding λ are separately determined and summed. Also possible is:

$$R = d / \lambda \qquad (3.8)$$

R = thermal heat resistance [m^2.K / W]

3.4 convection

Convection is a type of heat transfer in which the carrier changes its position. The carrier needs to be able to flow. This can only take place with liquids or gases. A distinction is made between free convection and forced convection.

Free convection

Free convection takes place because the heat decreases the density of the carrier. This will create a flow.

Forced convection.

In forced convection a mechanical flow of the carrier takes place, for example by a pump (liquid) or a fan (gas).

The amount of heat that is transferred by a carrier to a material through convection can be calculated in the following way:

$$Q = [A \times (T_r - T_m)] / (1/\alpha) \qquad (3.9)$$

The symbols mean:

α = heat transfer coefficient [W/(m^2K)]

A = surface area [m^2]

T_r = temperature of carrier [K]

T_m = temperature of material [K]

A few values of the heat transfer coefficient are included in Table 2. The value depends on the combination of material/carrier and the flow rate of the carrier in case of forced convection.

Table 2 Heat transfer coefficient (Kimmenaede, 2010)

Material/carrier	Heat transfer coefficient (α) [W/(m^2K)]
material <--> boiled liquid	2000 – 20.000
evaporated steam <--> material	8000 – 15.000
material <--> running liquid	1000 – 10.000
material <--> running gas	5 – 100
material <--> gas free convection	5 - 15

3.5 heat transfer at a spacer fabric

Heat transport often consists of a combination of radiation, conduction, and convection. The experiments will be based in a steady state condition.

Radiation

As described before in thermal equilibrium state, the absorptivity of a body equals its emissivity.

Textile materials are not transparent to long-wave radiation, therefore, the following applies:

$\tau = 0$

so: $\varrho = 1 - \varepsilon$

So, for the calculation of the amount of radiated heat, formula 3.6 can be applied.

Conduction and convection

The cross-section of a spacer fabric in a schematic overview is drawn in Figure 24. A knitting stitch is drawn as a rectangular block shape, for the front as well as the back of the spacer fabric. A monofilament yarn connects the front and the backside. This has schematically been drawn between the layers.

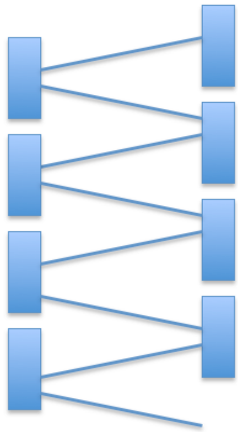

Figure 24 Schematic cross-section of spacer knitting

Heat transfer through the spacer fabric takes place through these 3 layers. Layer 1 is defined as the warm side. Layer 2 is the interlayer that connects the two outer layers. This consists of the monofilament yarn. Layer 3 is the layer placed at the cold side. Heat transfer by conduction takes place by the monofilament yarn. This depends of the surface of the yarn. Each stitch of layer 1 is connected with the stitch of layer 3 with 2 monofilament yarns. So the surface of the monofilament yarn for the test samples with a size of 20 x 30 cm, can be calculated in the following way:

$$A = \text{courses (20 cm)} \times \text{wales (30 cm)} \times 2 \times \pi \times r^2 \quad [m^2] \qquad (3.10)$$

r = radius of the monofilament

The convection in the spacer knitting can be calculated in the following way:

$$Q_{\text{convection}} = Q_{\text{total heat transfer}} - Q_{\text{conduction by monofilament}} - Q_{\text{radiation}} \quad [W] \qquad (3.11)$$

When measuring the total heat transfer it must be possible to calculate the convection in a spacer knitting. Then it is possible to see how much depends heat transfer of the surface (stitch length and/or raw material) and the thickness of the spacer knitting.

4. Literature review: test methods for thermal conductivity

4.1 Introduction

To be able to test the thermal conductivity of a material, you need to measure the heat flow through the material and the temperature difference on the material. There are several methods to measure the heat flow. If the heat flow is tested directly (e.g. the supplied power of the heat source) it is called an absolute measurement. If the heat flow is measured indirectly by comparing various materials with each other, it is called a comparative method.

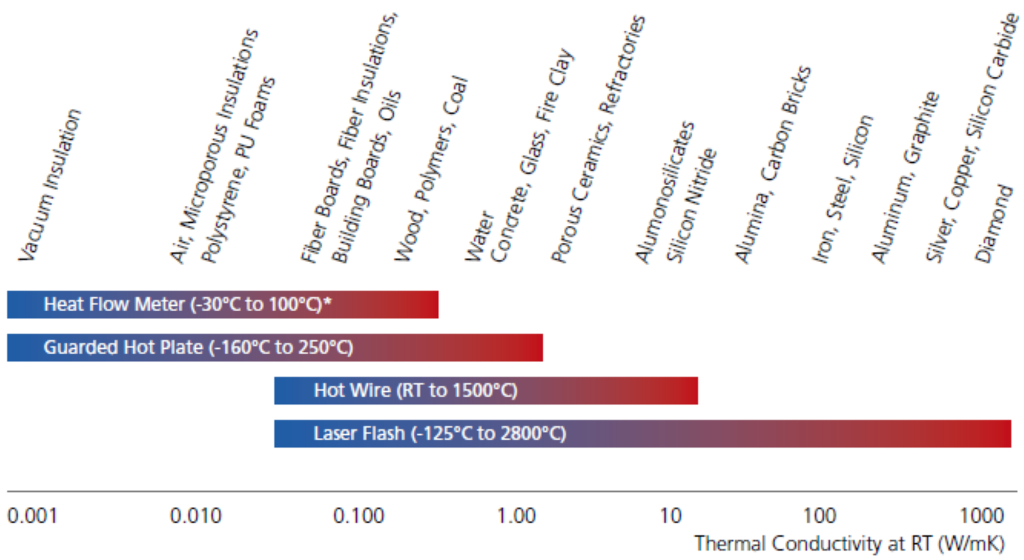

Figure 25 Thermal conductivity, methods and temperature (www.tainstruments.com, retrieved 28 November 2014)

There are a variety of standardized test methods. Each of these methods is suitable for a limited range of materials, depending on their thermal characteristics, and the temperature. (Figure 25) In addition, a distinction is made between steady state and transient methods.

If the temperature of the material does not change over time, the steady-state test method can be used. An advantage of this method is the easy signal processing. However, a proper design of the test equipment is essential. There are various standards:

- Standard test method for steady-state heat flux measurements and thermal transmission properties by means of the guarded-hot-plate apparatus (ASTM C177)
- Standard test method for steady-state thermal transmission properties by means of the heat flow meter apparatus (ASTM C518)
- Standard test method for evaluating the resistance to thermal transmission of materials by the guarded heat flow meter technique (ASTM E1530)
- EN 12667, "Thermal performance of building materials and products. Determination of thermal resistance by means of guarded hot plate and heat flow meter methods. Products of high and medium thermal resistance", ISBN 0-580-36512-3.

During transient test methods the measurement takes place during the heating process of the sample. An advantage of this is that measurements can be carried out faster. Measurements are often carried out using a plate or needle probe. Some of the generally known standards are:

- Standard test method for thermal conductivity of refractories by hot wire (platinum resistance thermometer technique) (ASTM C1113)
- Refractory materials –Determination of thermal conductivity –Part 1: Hot-wire methods (cross-array and resistance thermometer) (ISO 8894-1:2010)
- Plastics –Determination of thermal conductivity and thermal diffusivity–Part 2: Transient plane heat source (Hot Disk) method. (ISO/DIS 22007-2.2)
- Standard test method for determination of thermal conductivity of soil and soft rock by thermal needle probe procedure (ASTM D5334)

It is expected that the thermal conductivity coefficient will be situated in the area from 0,1 to 1,0 W/(mK) and that the temperature area will vary between -10 and + 40 °C. From the methods represented in Figure 25, the following methods can be considered:

- heat flow method
- guarded hot plate
- hot box
- hot wire
- laser flash
- needle probe
- photothermal

4.2 Steady state test method

4.2.1 Heat flow method

In accordance with the EN 12667 and ASTM E 1530 standards, this method is applicable to materials with a thermal conductivity coefficient between 0,007 and 1,0 W/mK and in a temperature area between -100 and +200 ^{o} C. (www.thermophysical.tainstruments.com) In this test method, a sample is pressed between 2 metal plates. (Figure 26) The plates have different temperatures.

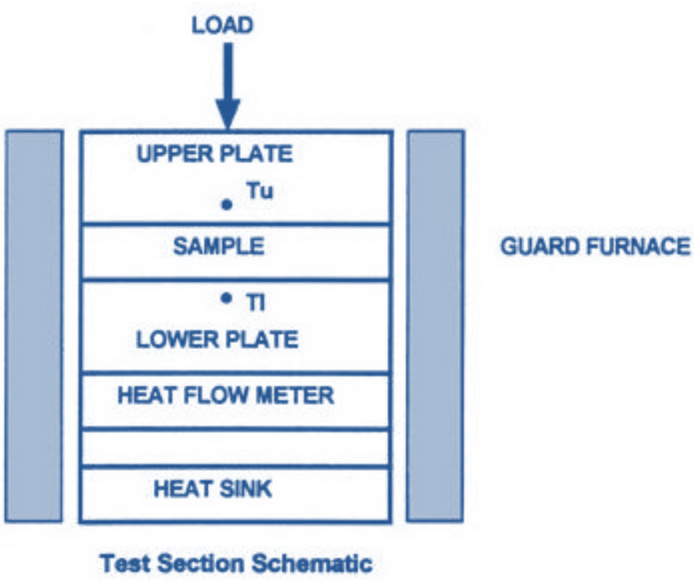

Figure 26 Heat flow method (www.azom.com, retrieved 28 November 2014)

By measuring the temperature difference on the sample, as well as the measured value of the heat flow, the thermal conductivity coefficient can be determined with the following formulas:

$$R_s = [\, F \cdot (T_u - T_i) \,/\, Q \,] - R_{int} \qquad (4.1)$$

$$\lambda = d \,/\, R_s \qquad (4.2)$$

R_s = thermal resistance of the sample	[m^2.K / W]
F = heat flow transducer calibration factor	[-]
T_u = temperature, upper plate	[K]
T_i = temperature, lower plate	[K]
Q = heat flow transducer output	[W]
R_{int} = thermal resistance of interface	[m^2.K / W]
λ = thermal conductivity coefficient	[W/(m.K)]
d = thickness of sample	[m]

4.2.2 Guarded hot plate method

Using the guarded hot plate method, two (similar) samples are placed on both sides of a heated plate. (Figure 27) On the other sides of the samples, a cold plate is placed. The entire unit is placed in an insulated casing. The temperature of the warm and cold sides is measured, as is the power that is supplied to the heating unit.

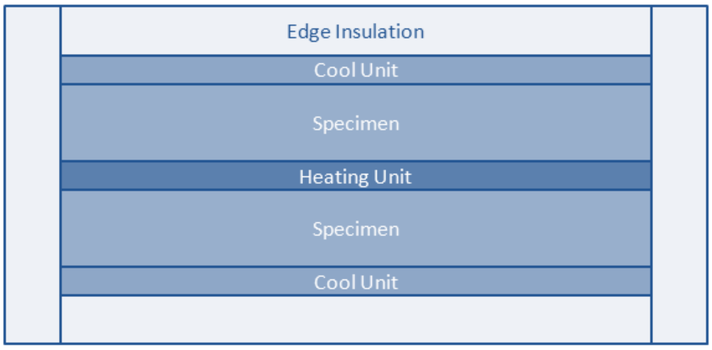

Figure 27 Guarded hot plate method

At the moment of reaching the steady state, the thermal conductivity coefficient can be calculated using with the following formula:

$Q = \lambda \cdot A \cdot (T/d)$

The symbols mean:

Q = heat flow	[W]
λ = thermal conductivity coefficient	[W/m.K]
A = surface area	[m^2]
T = temperature difference	[K]
d = thickness of sample	[m]

The guarded hot plate method is suitable for materials with a thermal conductivity coefficient between 0,0001 and 2, and a temperature range from -180 to + 1000 °C

4.2.3 Hot box method

The design and operation of the hot box is described in the standard EN ISO 8990. (Appendix 2) This test method can be executed in accordance with the principle of an absolute or comparative method. The calibrated hot box works according to the comparative method, the guarded hot box Figure 28 works according to the absolute method.

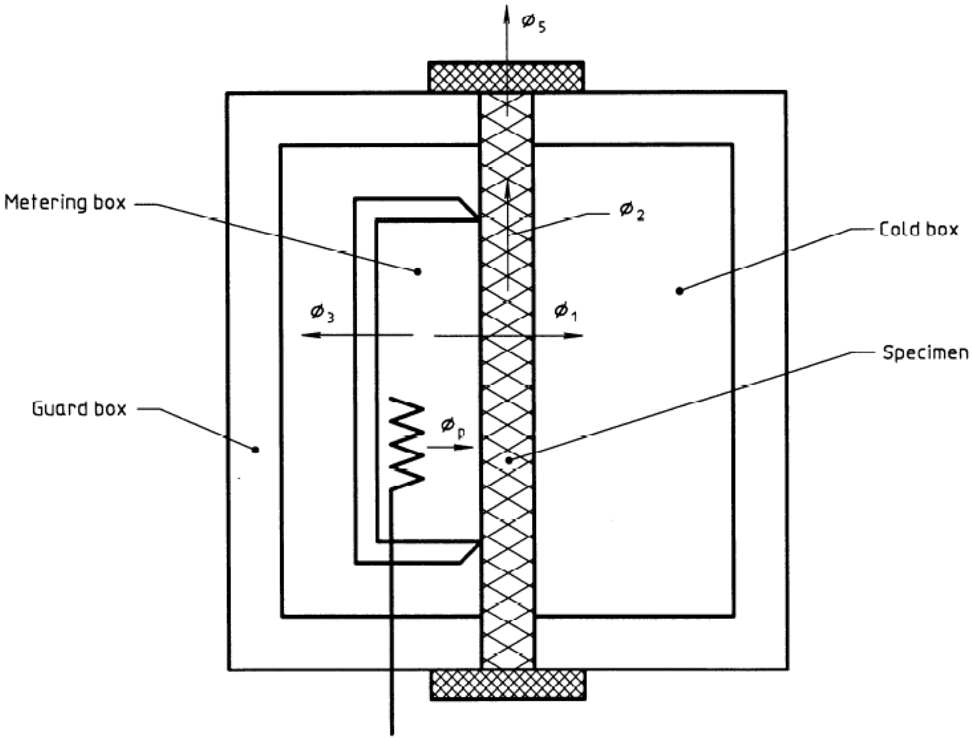

Figure 28 Hot box (EN-ISO 8990)

The temperature range lies between -20 and +40 ^{o} C. The thermal conductivity coefficient lies between 0,2 and 5 W/mK. The hot box test method is specifically developed for (large) non-homogeneous structures. These are placed between a warm and a cold room. Sensors measure the temperature. Also, the power that is supplied to the heat source needs to be registered.

4.3 Transient testing

4.3.1 Hot wire method

The hot wire method is a transient measuring technique, based on measuring the increase of temperature at a certain spacer from a hot wire wrapped in the test material. (http://www.tpl.fpv.ukf.sk) Assuming that the heat source has a constant heat emission across the entire length of the test sample, the thermal conductivity can be directly determined from the changes in temperature over a specific interval of time.

The method is based on the assumption that the hot wire is an ideal, infinitely thin and long heat source, completely surrounded with a homogeneous and isotropic material with a constant initial temperature. (Figure 29) If q is the constant amount of heat production per time unit and per length unit of the hot wire (W.m-1), a radial heat flow will occur around the wire, from moment t = 0. The temperature will increase ΔT(r,t) in radial direction r (Figure 29) from the heat source according to the following formula:

$$\Delta T(r, t) = Q/(4\pi\lambda) \ln((4at)/(r^2C))$$

The symbols mean:

λ= the thermal conductivity coefficient	$[W.m^{-1}.K^{-1}]$
a = thermal diffusivity	$[m^2.s^{-1}]$
$a=k/\rho c_p$, ρ is the density of the test material	$[kg.m^{-3}]$
c_p is the heat capacity of the test material	$[J.kg^{-1}.K^{-1}]$
Q = heat flow input	[W]
$C = \exp(\gamma)$,	γ = 0,5772157 (Euler's constant)

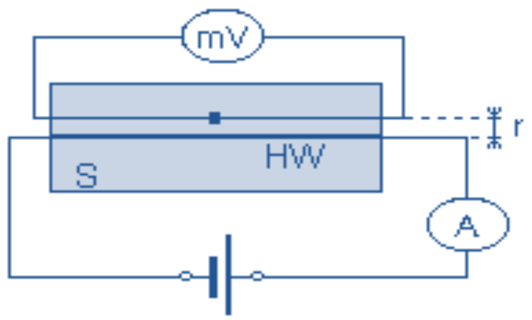

Figure 29 Hot wire method (www.tpl.fpv.ukf.sk, retrieved 23 November 2014)

4.3.2 Laser flash method

The flash method is a technique for measuring thermal diffusivity of materials with a moderate to good thermal conductivity (approximately > 0.5 W/m K) perpendicular to the surface. In-plane measurements can be carried out with a 'point' energy source and radial temperature measurements across the surface. The basic method is based on measuring the increase of temperature on the back of a thin disk, caused by a short energy pulse on the front. The sample is placed in an oven and heated up to a certain temperature. (Figure 30) A short pulse (1 ms or less), originating from a laser or a flashlight, radiates towards one face of the model. The resulting increase of temperature on the rearmost surface (and/or the front side in some cases) is measured with a thermocouple or with an IR-detector (HgCdTe, InSb or another one depending on the temperature range). The thermal guide number is calculated based on this temperature versus time curve and the thickness of the sample. Knowledge about the energy that is absorbed and the emissivity is not required.

The sample holder is designed in such a way that there is a minimal thermal contact with the sample, and to screen off the diffused light of the laser beam to the IR-detector. Both sides of the model should be covered with a thin layer of graphite, or another highly radiation-absorbing material to have both sides optimally absorb the energy impulse and heat radiation emission.

Boundary conditions:

1. The material that is to be tested needs to be level and even.

2. If the materials are non-homogeneous, only samples with a limited inhomogeneity (granules or pores etc. < 0.05 thickness) can be measured because of the small sizes of the sample (on the condition that the sample is representative for the material).

3. The sample should be non-transparent for the wavelength of the laser; any transparent samples should be coated.

The thickness of the sample should be selected based on the pulse width of the laser and the expected thermal coefficient.

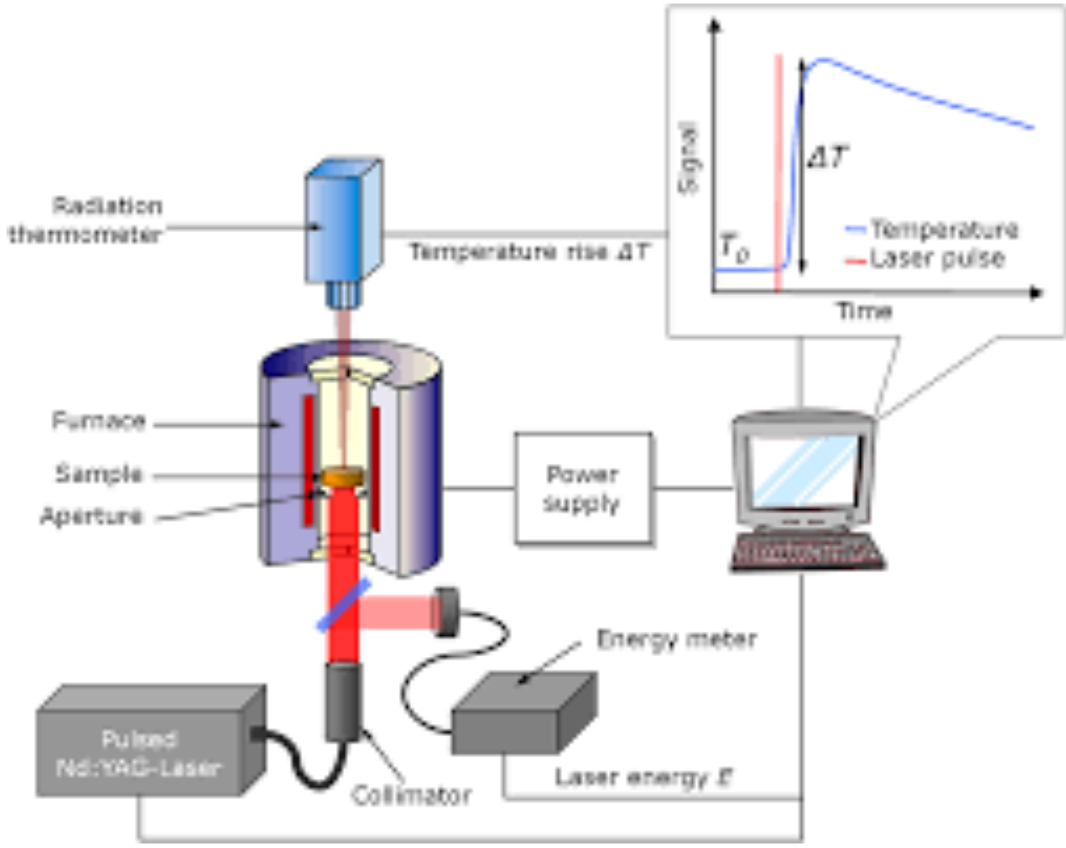

Figure 30 Laser flash method (www.link.springer.com, retrieved 18 February 2016)

4.3.3 Needle probe method

The hot-wire technique has been the most often used method for many years to measure the thermal conductivity according to the transient test method. Recently a modification of this technique has been developed: the needle probe method. At this moment, this technique is a test method with a good accuracy (< 5%), thanks to continual improvements.

An increasing expansion of newly developed materials has caused the increase in demand for the development of a new test method. Speed is especially important, as is being able to use smaller and easily produced samples, and being able to measure several properties at the same time.

Resulting from this is the development of various test methods, which are all based on the same principle as the hot wire, and hot plate test methods. They can measure one or more thermo physical properties of high density homogeneous solid materials. Various versions of tests have been developed, based on this test method, that make it possible to test very thin films, very good conductors, and anisotropic materials.

These new methods are called 'Contact Transient Methods.' Thanks to their simplicity in design and realisation, these popular methods are often applied. Important for this technique is the verification of the reference materials. These are required for the calibration and may adversely influence the results to a considerable extent. In general, this method can be applied in a broad temperature range and for a large thermal conductivity range.

Special attention is required for the following: the input power levels and the duration of testing need to be carefully selected. Also, the hardware for the experiment needs to be of high quality. (Figure 31) A computer has to be used for data processing and analysis.

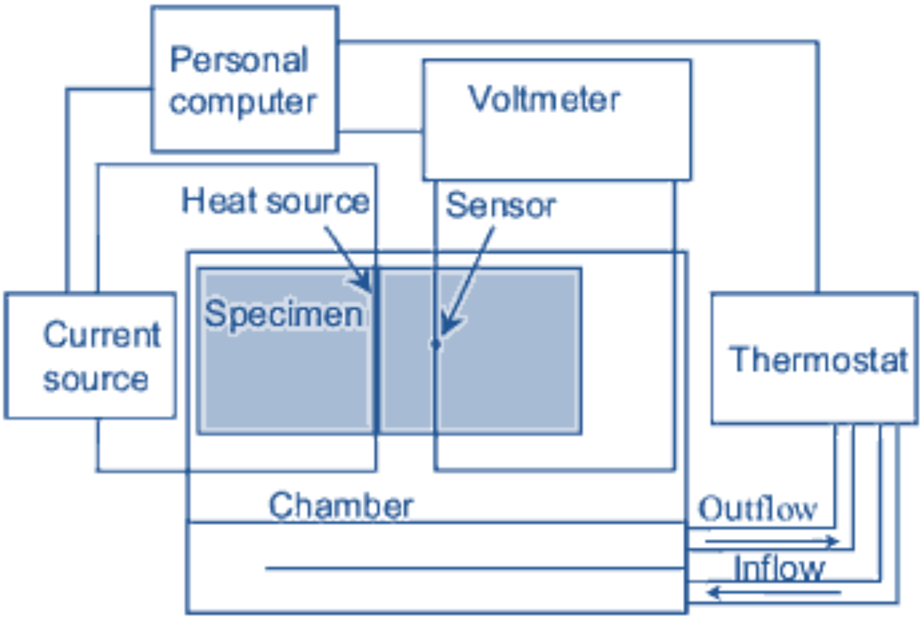

Figure 31 Needle probe method (www.neil-brown.com, retrieved 29 November 2014)

4.3.4 Photo thermal method

The photothermal method is based on the principle of generating heat waves on the surface of the sample, (Figure 32) in which the intensity is modulated. The depth that the wave penetrates the sample, depends on the thermal conductivity and the modulation frequency of the light intensity. The (laser) light causes temperature changes on the surface of the object that is tested. The resolution lies in the order of a few micrometres when

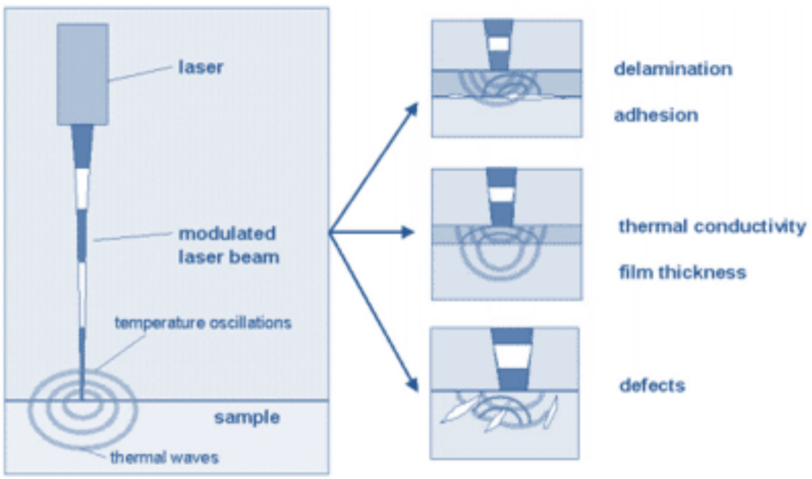

Figure 32 Photo thermal method (www.iam.kit.edu, retrieved 4 December 2014)

using a light beam from a laser, since only the heated area contributes to the measured signal. The thermal waves can be analysed by a variety of measuring equipment.

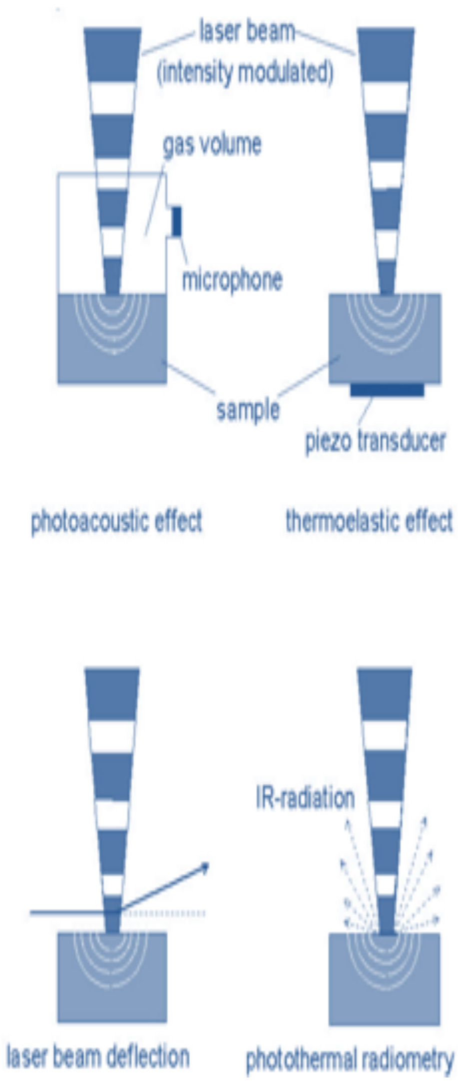

Photo acoustic: temperature oscillations induce pressure oscillations in a gas volume. A microphone detects these pressure variations. (Figure 33 at the top left)

Thermo elastic: temperature oscillations induce elastic waves in the test material. A piezoelectric transducer detects these waves. (Figure 33 at the top right)

Laser beam deflection: temperature oscillations cause a change in the refractive index of light as a result of which a light beam bends off under a specific angle. (Figure 33 at the bottom left)

Photo thermal radiometry: temperature oscillations cause a reflected infrared radiation that can be measured by an infrared detector suitable for that purpose. (Figure 33 (at the bottom right)

Figure 33 Variety of measuring (www.evitherm.org retrieved 6 December 2014)

The phase shift and the amplitude of the thermal waves are a function of the modulated laser light. With a computer model suitable for that purpose, this information can be converted into the heat coefficient. The material that is to be tested needs to be level and opaque. Opaque materials first need to be coated. An example of a possible testing set-up is shown in Figure 34.

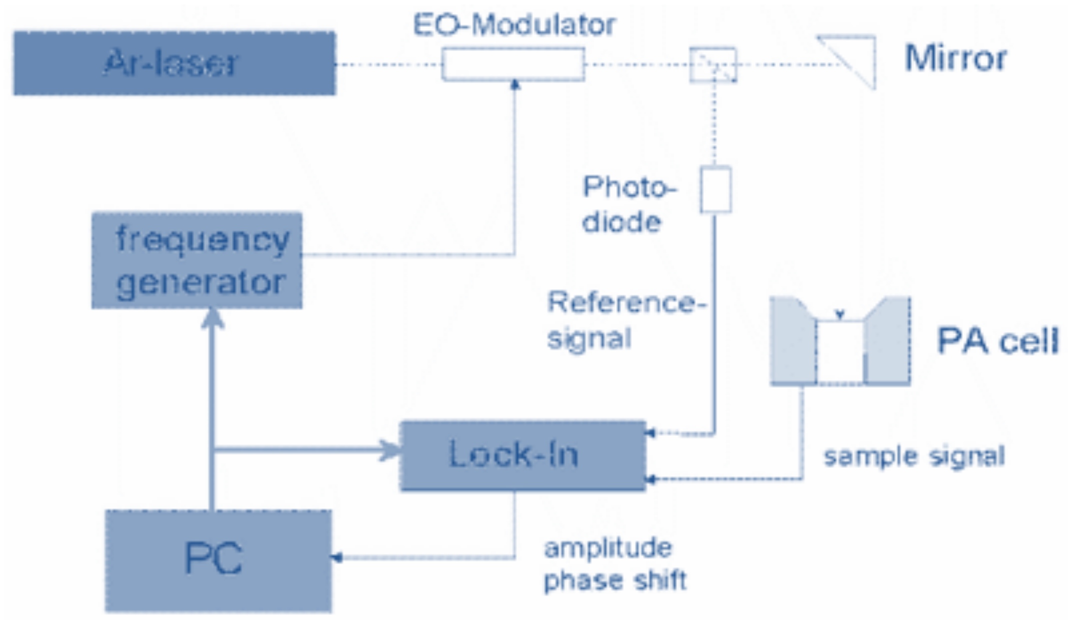

Figure 34 Testing set-up for photo thermal method (www.evitherm.org retrieved 6 December 2014)

4.4 temperature measurement methods

Temperature and heat flux are strongly related because, as will be shown later, heat flux measurement methods are based on accurately measuring temperatures in a well-defined configuration. The temperature measurement methods (Pallas-Areny, 1991) can be divided into point measurement methods and field measurement methods. The best-known point measurement methods are the thermocouples and the resistance thermometers. The most important field measurement methods are: infrared thermography, liquid crystal thermography and light/laser induced fluorescent method.

4.4.1 Field measurement methods

4.4.1.1 Infrared thermography

This method is based on measuring the amount of emitted radiation energy in the infrared wavelength area (1 μm –100 μm). For temperatures of an object between 300 K and 2000 K, the maximum amount of radiation energy is emitted in this wavelength area. If the radiation properties of the object are well known, such as the spectral dependent emission coefficient, the local temperature can be determined from the emitted radiation energy.

4.4.1.2 Liquid crystal thermography.

This method is based on selective reflection of white light. Certain liquid crystals show a layered structure, of which the layer spacer depends on the temperature. Now, by bringing such crystals in a white light field, selective reflection will take place, which makes only one colour observable to the observer (a camera or the naked eye). This colour, then, is a measurement for the temperature.

4.4.1.3 Light/laser induced fluorescence.

This method is based on the temperature-dependent fluorescence properties of certain substances, such as rhodamine B. Contrary to the previous method; in this case a monochromatic light field is applied using a laser. Molecules in the light field will be affected under absorption of photon energy. After that, they will fall back to the ground state under transmission of light (fluorescence). Since the fluorescence properties depend on the temperature, the fluorescence intensity is a measurement for the temperature.

4.4.2 Point measurement methods

4.4.2.1 Thermocouples.

The working of a thermocouple is based on the so-called 'Seebeck effect'. The physicist T.J. Seebeck discovered in 1821 that there is an electromotive force (EMF) at the junction of two different materials. L.C.A. Peltier discovered in 1834 that when two dissimilar metal threads are joined together, there will be a current if both ends of the thread have a different temperature. This is the basis of how a thermocouple works. The junction through which the temperature is measured is called the hot junction. The open end is called the cold junction. The temperature measured is a differential measurement, i.e. the difference in temperature between the hot and cold junction is measured. The cold junction needs to be kept at a reference temperature (e.g. melting ice). In addition, the temperature of the cold junction can be measured electronically and processed, with electronics for example, in the final measurement. Thermocouples can be produced using various combinations of metals. The combination determines the measuring area and the accuracy. An often-used thermocouple is type K, which consists of the metals NiCr (Nickel-Chromium) and NiAl (Nickel Aluminide). This couple has a measuring range from – 200 to + 1200 ^{0}C. There are thermocouples that can measure up to approx. 2300 ^{0}C. Thermocouples can be very small, making for a very fast response time.

4.4.2.2 resistance thermometers

The principle of a resistance thermometer is based on the temperature dependence of the resistance of materials. The two most important applied types of materials are the metals and the semi-conductors.
Thermometers in which a metal is applied are called metal resistance thermometers, and thermometers in which a semi-conductor material is applied are called thermistors.

Metal resistance thermometers

Metals have a positive temperature coefficient, which means that the electric resistance becomes larger as the temperature increases. The most applied metal resistance thermometer is the Pt-100. (also called **RTD**, as in **R**esistance **T**emperature **D**evice). The metal used is platinum, which has a nominal resistance of 100 Ω at 0 ^{o}C. Another metal used is nickel.
A Pt-100 element is created by winding a very fine platinum thread around a glass or ceramic core. The platinum can also be applied in the form of a foil or a very thin film. By means of this technique, sensor can be made much smaller than thread-wound resistors (Figure 35).

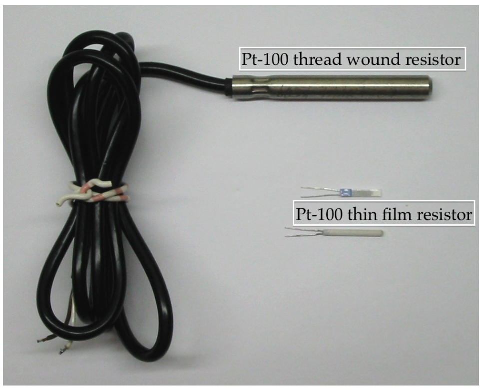

Figure 35 Pt-100 thread-wound resistor (above) and Pt-100 thin film resistor (middle/under) (www.wikipedia.org retrieved 16 December 2014)

To be able to measure the change in resistance, a current is needed through which the difference in voltage can be measured. For a platinum sensor, the current intensity varies from 1 to 10 mA. This results in a sensitivity of 0.4 to 4 mV/K. Pt-100 sensors have no hysteresis effects and can be applied between -200 and + 850 ^{o}C. In case of temperature differences that are not too large, the resistance curve is nearly linear.

For platinum, the resistance as a function of the temperature is in the range between 0 ^{o}C and 850 ^{o}C can be calculated as follows:

$$R(t) = R_0 (1 + A (T - T_0) + B (T - T_0)^2)$$

The values of the constants A and B are:

A: $3.90802 \cdot 10^{-3}$

B: $-5.80195 \cdot 10^{-7}$

For accurate measurements, the influence of the resistance of the connection wires, as a result of the ambient temperature needs to be taken into account. This can be prevented using a three or four wire circuit (Figure 36).

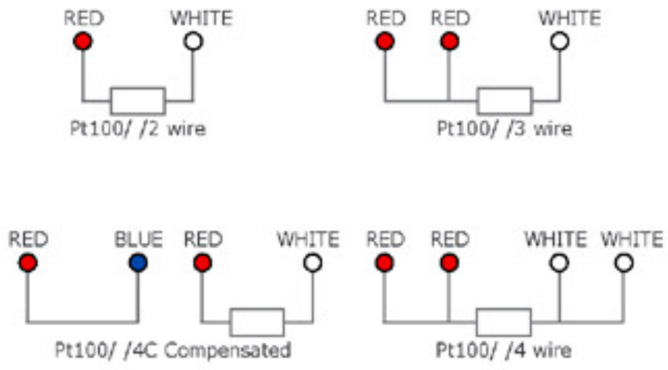

Figure 36 Four wire circuit (www.sensorland.com, retrieved 4 April 2015)

Thermistors

In a thermistor is a semiconductor material, of which the resistance depends on the temperature.
The semiconductor material can have a positive or negative temperature coefficient. (PTC or NTC). The sensitivity of thermistors lies around 50 mV/K, for which the relation between the temperature and the resistance is not (entirely) linear. Thermistors have a temperature range up to 100 ^{o}C. Thermistors are physically small (Figure 37) and therefore have a short response time.
To compensate for the non-linear relation, an electronic circuit needs to be applied. This circuit can be added to the sensor as an Integrated Circuit (IC). Because of the size of the IC sensor, this has a longer response time. Though, the temperature range is equal to the NTC thermistor.

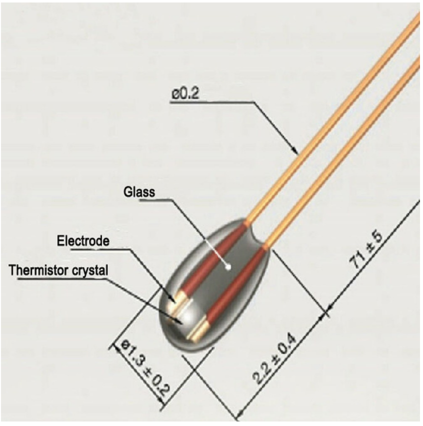

Figure 37 Thermistor (www.aliexpress.com retrieved 19 January 2016)

5. Experimental

5.1 Design of testing set-up

For the design of the testing set-up, it is necessary to look at which testing method is suitable for the thermal conductivity, and also which temperature sensors need to be applied. Requirements for the design are: simplicity, price, applicability of various materials, and in future research being able to test the influence of the flow of air along the material that is tested.

5.1.1 Thermal conductivity test method

To test the thermal conductivity, many methods are available. In chapter 4.2 and 4.3 several methods are described that seem suitable for testing the expected temperature range and thermal conductivity. An important distinctive feature for the test methods is whether the temperature remains constant during testing, or if it changes over time. Basically, it is possible to keep the temperature constant. The steady-state test methods could then be used. An advantage of this method is the easy signal processing. However, this type of test method requires a well-considered and proper design of the testing set-up. The following test methods can be considered: heat flow method, hot plate method, and hot box method. The hot box method can be divided into the guarded hot box and the calibrated hot box methods. The calibrated hot box test method is the only test method in which one side is aimed outwards. Because the exterior is directly accessible, it is also possible to look at how the material behaves when there is an air flow alongside the test material. To measure the thermal conductivity, when it is possible to have an air flow circulating past the test material, the calibrated hot box method seems the most suitable.

5.1.2 Selection of test sensors

To calculate the thermal conductivity, the temperature needs to be tested on both sides of the material to be tested. The accuracy of the result does not only depend on the accuracy of the test sensor: It is also important to observe any possible temperature differences that can occur on the test material. This means that it is necessary to measure on various spots. Several test sensors are therefore required.

The temperature range measured is limited. This is expected to be between 0 ^{o}C and 60 ^{o}C.

The sensors need to be applied onto the knitted fabric. This requires the sensors to be small enough to make sure that the sensor does not cover the material, and sufficiently light-weight to make sure it can be applied easily on the textile material.

Since temperatures need to be measured in the hot box, the field test methods are not suitable for this purpose. That is why the advantages and disadvantages of thermocouples, metal resistance thermometers and thermistors have been examined. The test accuracy of thermocouples, depending on the type, lies between 0.5 and 2 ^{o}C. The accuracy of a Pt100 sensor, for example, is considerably higher if the influence of the connection wires (four-wire circuit) is taken into account. A thermistor can also achieve a higher accuracy if the non-linear behaviour is compensated with an electronic circuit. The latter implies not only a higher cost, but also a larger sensor with a longer response time. The price is also much higher for a four-wire Pt100 circuit than for a type K thermocouple, for example. Considering the number of sensors that need to be placed, the limited temperature range, and the requirements of the dimensions the use of thermocouples is preferable. The aim is to look for suitable test equipment with a reasonable accuracy and an acceptable price tag.

5.1.3 Design of testing set-up

To test the thermal conductivity, a calibrated hot box is designed in accordance with ISO 8990 standard. In Appendix 3 Design of the hot box the design is drawn. In Figure 38 the hot box is shown, as built in accordance to Appendix 3 Design of the hot box.

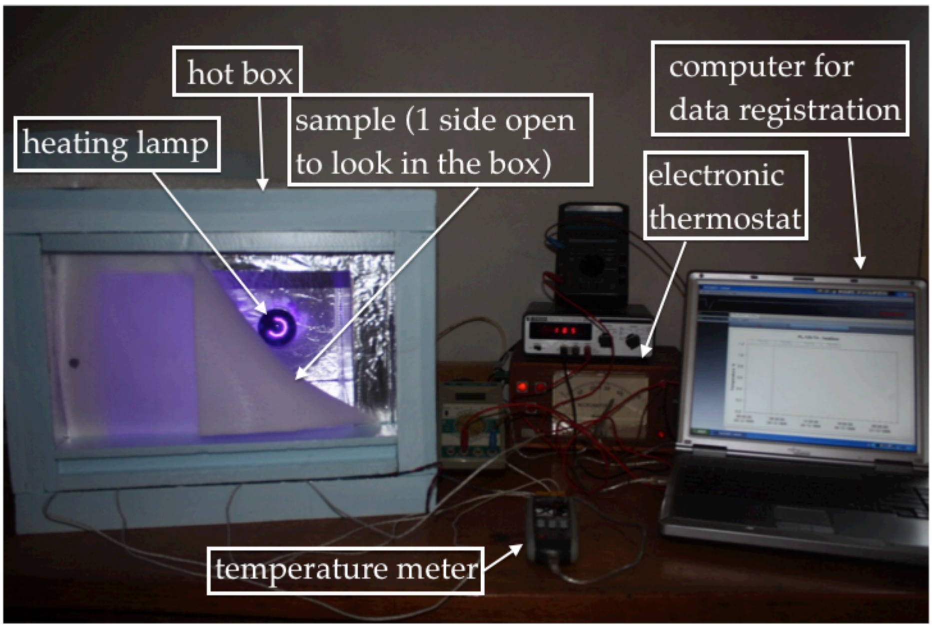

Figure 38 First prototype of the hot box

To keep the heat loss as low as possible, it is necessary to select a material with a lambda as low as possible. In Table 3 the most common insulating materials are given. Styrofoam XPS Roofmate is applied as an insulating material (λ = 0.027) with a thickness of 5 cm. The insulating material was doubled so the total thickness of all the walls of the hot box is 10 cm.

Table 3 Heat resistance of insulating material (www.isover.com retrieved 2 November 2014)

Insulating material	Heat resistance (λ)
Rock wool	0.035
Glass wool	0.040
Expanded polystyrene EPS	0.035
Expanded polystyrene XPS	0.027

The 20 x 30 cm test material can be applied on the front side. The front side can also be closed with a special Styrofoam sheet made to size. This makes it possible to calibrate the hot box. The inside is completely coated with aluminium foil. All seams are sealed to have as little heat loss as possible.

The heating elements of the hot box are 2 heat lamps (total capacity of 150 Watts), which are placed against the back wall. These are covered by an aluminium plate to prevent warming up of the test material due to radiation heat from these lamps. The lamps can be connected in parallel or in series, depending on how much heat is required.

The temperature in the hot box can be adjusted continuously using an (self-constructed) electronic thermostat. The provided power to the heating lamps can be measured by means of a power meter. The power meter that was selected is a meter from the manufacturer Voltcraft energy logger 4000. (Figure 39)

Figure 39 Voltcraft energy logger (www.voltcraft.nl retrieved 3 December 2014)

This meter has a measuring range of 0.1 to 3500 Watt with an accuracy of ± 1%. This meter can measure the real power and the apparent power (cos Ψ).

To measure the temperature, 2 temperature gauges are used, from the brand Voltcraft PL-125-T4USB, (Figure 40) which all contain 4 thermocouples. In total, the temperature can be measured at 8 locations. The measuring accuracy is 0.15%.

Figure 40 Voltcraft temperature meter (www.voltcraft.nl retrieved 3 December 2014)

5.2 Test materials

5.2.1 Knitting machine

In The Netherlands there isn't any warp knitting factory. So it was not possible to knit samples with warp knitting technology.

For the weft knitted fabrics a Monarch V7 double bed 30'' circular knitting with a gauge 20", machine was used. (Figure 41)

Figure 41 Monarch knitting machine

The speed of the knitting machines is deliberately kept low at 18 RPM. All knitting machines have yarn storage feed devices of the Memminger type, so that the yarns can be fed in a controlled way. This is adjusted with a quality-adjusting pulley. The adjustment of the quality-adjusting pulley (QAP) determines the stitch size. It should be noted that the yarn tension is adjusted with the stitch cam at 3 cNewton. After this, a test sample is knitted, and subsequently the amount of yarn per rotation is measured in the lab. One thread should therefore be ravel out per type of yarn. This is measured on a special measuring rod. With this data, the gauge and diameter of the knitting machine, the stitch size can be calculated.

5.2.2 Test materials

Eight different knitted fabrics have been tested in total. The spacer weft knitted fabrics vary in stitch size, material composition, fabric and yarn thickness. The technical data of all tested knitted fabrics are included in Appendix 4 till 11, which also describe a unique number that is allocated to the various qualities.

5.3 Prototyping and operation instructions of the hot box

5.3.1 Prototyping the hot box

The first time the position of the hot box was horizontal, this means the open side was at the front. During measurement there where differences in temperature at the lower and upper side of the samples. A new set up was required: the open site was placed at the top. (Figure 42)

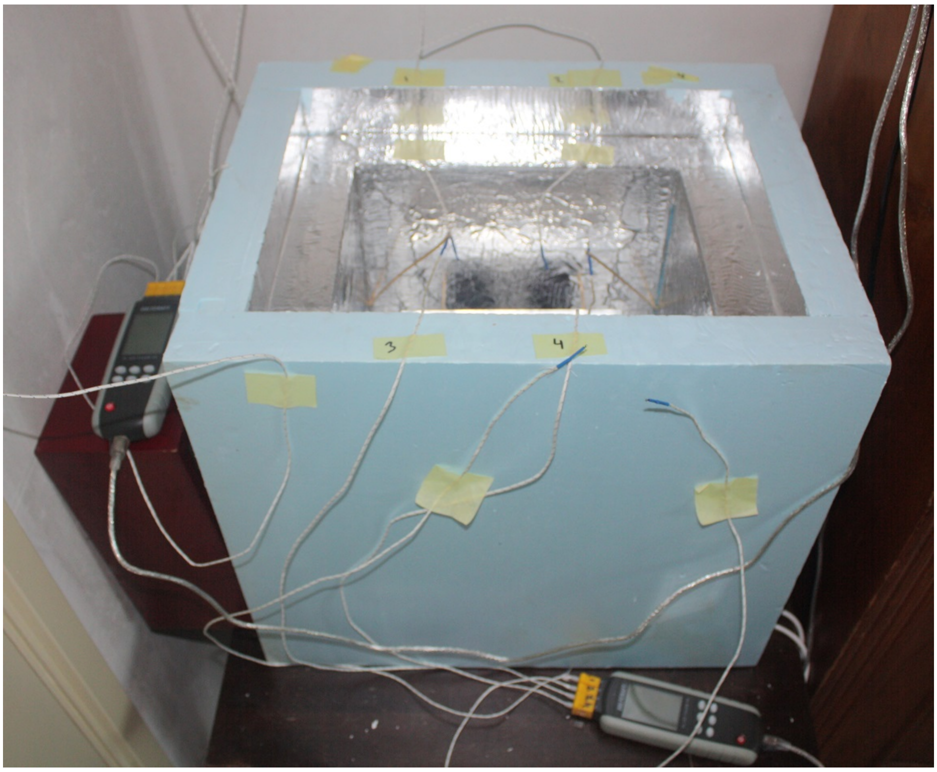

Figure 42 Final position of the hot box

Some new measurements were done. Now there were differences in temperature at the samples that was of the direct heating of the heating lamps. The temperature in the middle of the sample was higher than the temperature at the border. The solution was masking the heating lamps with an aluminium baffle. (Figure 43) After measuring the temperature overall, no differences were found.

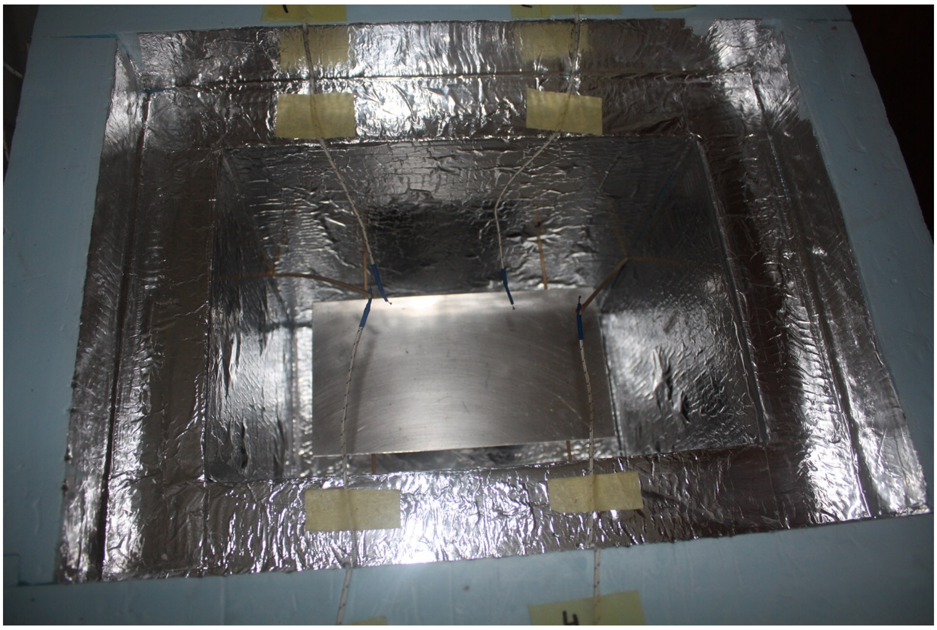

Figure 43 Baffle masking the heating lamps

At first 2 heating lamps were fitted in the box. It was possible to switch them in series or in parallel. After testing it seems that 2 lamps serial gives enough power for the maximum temperature. The advantage of 2 lamps is a better dispersion of the heat in the hot box.

All the tests were done in this way.

5.3.2 Calibrating the hot box

Before using the hot box, it needs to be calibrated. A difference in temperature between the inside and outside of the hot box gives always a heat flow, called power loss. It is important to know how much the power loss is, because it is necessary to rectify the results of the measurements with this value. It is possible to measure or to calculate the power loss.

For the measurement, the open side of the hot box needs to be closed off with a special (very thick: 30 cm) insulating plate. Next, the hot box is heated up to the required temperature. When the temperature has been reached, this needs to be kept at a constant by way of electronic control. At that moment, the measurement of the provided power can be started. This is done at several different temperatures. The values can be found in Figure 44.

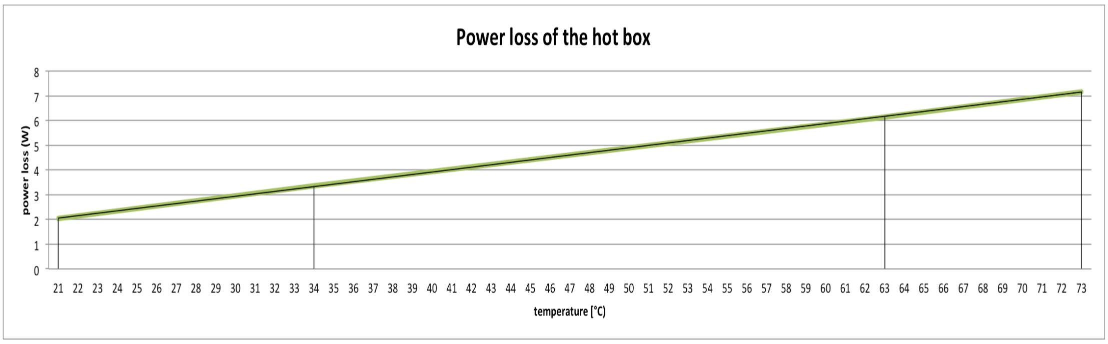

Figure 44 Relation between temperature and power loss of the hot box

The temperature in Figure 44 is the difference temperature between inside the box and the ambient temperature. These values of power loss need to be used as correction numbers when testing the materials.

5.3.3 Description of the test procedure

The dimensions of test material need to be 20 x 30 cm. The sample is clamped at the open side. Next, the hot box is adjusted to the desired power. Once the temperature remains constant, this can be read out. The temperature is measured on two places at the sample, inside and outside. Also the temperature in the box and the ambient temperature were measured.

6. Results and discussion

Heat resistance of the fabrics

In total 8 different knittings have been tested for thermal conductivity with the hot box. By choosing 3 different power levels (approximately 10, 20 and 40 Watt) the knittings have been tested at different temperatures. In appendix 4 through 11 the measuring results are shown graphically per tested sample. The 3 different power levels are shown in separate graphs. In each graph has been drawn:

- average temperature in the hot box (green line)
- average temperature inside fabric (dark blue line)
- average temperature outside fabric (purple line)
- ambient temperature (light blue line)
- deviation (orange line)

Every 2 seconds the temperature is measured. All temperatures have been measured with 2 sensors after which the average has been calculated. The moment the measurement is started the temperature will rise. This increase diminishes gradually due to the fact that the temperature of the hot box will almost equal the ambient temperature. If this would be continued endlessly the following will apply:

applied heat = heat flow through the test material + ceded heat to the ambiance by the hot box.

Then a stationary state applies. However, in actual practice the duration of the measurement will have to be limited. In order to know when a measurement can be stopped it has been calculated to what extent the value of the heat resistance changes in the course of the measurement. This has been carried out on a random basis with quality P11680. At a constantly applied power (Appendix 10 Spacer knitting P11680; Figure 73 Test results P11680 19,8 Watt) the heat resistance has been calculated at different points of time. The measured temperatures and the appurtenant calculated heat resistances are shown in Table 4.

Table 4 Calculated heat resistance at several times

P11680, 19,8 Watt	T 1	T 2	T 3	T 4	R
18:15	38,9	33,4	34,8	28,6	0,0007
18:30	52,5	47,6	44,2	33,3	0,0013
18:45	56,5	54,6	46,9	34,8	0,0014
19:00	58,2	57,7	48,1	35,4	0,0015
19:15	59,6	59,2	49,4	35,4	0,0016
19:30	60,5	60,3	49,9	36,7	0,0016
19:45	60,8	60,8	49,9	36,7	0,0016
20:00	61,1	61,2	50,4	36,8	0,0016
20:15	61,6	61,5	50,8	37,2	0,0016
20:30	62,2	61,9	51,2	37,3	0,0016
20:45	62,2	62,2	51,4	37,3	0,0016
21:00	62,2	62,2	51,7	37,4	0,0016

T 1: average temperature in the box [°C]

T 2: average temperature in the last 20 minutes [°C]

T 3: average temperature inside surface [°C]

T 4: average temperature outside surface [°C]

R: calculated heat resistance (x 10^{-3}) [m^2.K / W]

The heat resistance is calculated up to 1/100. The acceptable deviation is 1%. This maximum deviation is achieved if the temperature has not increased more than 0.1% over the average of the last 20 minutes. (Table 4 Calculated heat resistance at several times) It can therefore be assumed that the state is stationary. In all graphs in the annexes an orange line indicates this. If the deviation is more than 0,1% this will be represented by the Y-axis value of 0. If the deviation is less than 0,1%, the orange line will take on a positive value. The graphs in appendix 4 through 11 show that the deviation is not less than 0,1% for one moment. The moment the deviation remains less than 0,1% it is assumed that the stationary state has been reached. After 30 minutes the temperatures are read from both the inside and the outside of the fabric. With the aid of these values and the measured power applied, the total heat resistance of the fabric can be calculated.

Heat resistance P10070

The spacer knitting P10070 (Appendix 4 Spacer knitting P10070) is a standard spacer knitting with a 2,36 mm thickness. At 3 different applied power levels (Q1, Q2 and Q3) the following temperatures have been measured: T in the hot box; T inside fabric; T outside fabric and T ambient. The measuring results are specified in Table 5 P10070 measuring results.

Table 5 P10070 measuring results

P10070	Q1= 11,2 Watt	Q2= 20,8 Watt	Q3= 41,5 Watt
T box	43,0	61,3	91,8
T inside fabric	36,1	49,4	75,1
T outside fabric	27,8	32,4	44,9
T ambient	20,6	20,6	20,7

For each power level a correction needs to be applied depending on the temperature difference between T box and T ambient. (ΔT) (Table 6)

Table 6 P10070 corrections

P10070	Q1	Q2	Q3
ΔT	22,4	40,7	71,1
correction [Watt]	2,2	3,9	6,9
nett heat flow [Watt]	9,0	16,9	34,6

With formula 3.8 the total heat resistance can be calculated:

Q1 = 9,0 = ((0,2 x 0,3) x 8,3) / R

R = 0,055 m^2.K / Watt

Q2 = 16,9 = ((0,2 x 0,3) x 17,0) / R

R = 0,060 m^2.K / Watt

Q3 = 34,6 = ((0,2 x 0,3) x 30,2) / R

R = 0,052 m^2.K / Watt

Heat resistance P10086

The spacer knitting P10086 (Appendix 5 Spacer knitting P10086) is a spacer knitting with a 4,72 mm thickness, which is the maximum attainable on the knitting machine used. The measuring results are listed in Table 7.

Table 7 P10086 measuring results

P10086	**Q1= 12,0**	**Q2= 20,9**	**Q3= 41,2**
T box	49,2	64,9	96,8
T inside	42,4	55,7	81,2
T outside	28,8	34,4	43,3
T ambient	20,0	20,1	20,4

For each power level a correction needs to be applied depending on the temperature difference between T box and T ambient. (ΔT) (Table 8)

Table 8 P10086 corrections

P10086	Q1	Q2	Q3
ΔT	29,2	44,8	76,4
correction [Watt]	2,8	4,3	7,4
nett heat flow [Watt]	9,2	16,6	33,8

With formula 3.8 the total heat resistance can be calculated:

Q1 = 9,2 = ((0,2 x 0,3) x 13,6) / R

R = 0,089 m^2.K / Watt

Q2 = 16,6 = ((0,2 x 0,3) x 21,3) / R

R = 0,077 m^2.K / Watt

Q3 = 33,8 = ((0,2 x 0,3) x 37,9) / R

R = 0,067 m^2.K / Watt

Heat resistance P11081

The spacer knitting P11081 (Appendix 6 Spacer knitting P11081) is a spacer knitting that has a different density at the front and at the back. The results are listed in Table 9.

Table 9 P11081 measuring results

P11081	Q1= 12,1	Q2= 21,3	Q3= 41,7
T box	46,3	62,4	92,3
T inside	37,9	50,3	72,8
T outside	30,5	35,6	46,8
T ambient	21,0	20,8	21,3

For each power level a correction needs to be applied depending on the temperature difference between T box and T ambient. (ΔT) (Table 10)

Table 10 P11081 corrections

P11081	Q1	Q2	Q3
ΔT	25,3	41,6	71,0
correction [Watt]	2,5	4,0	6,9
nett heat flow [Watt]	9,6	17,3	34,8

With formula 3.8 the total heat resistance can be calculated:

Q1 = 9,6 = ((0,2 x 0,3) x 7,4) / R

R = 0,046 m^2.K / Watt

Q2 = 17,3 = ((0,2 x 0,3) x 14,7) / R

R = 0,051 m^2.K / Watt

Q3 = 34,8 = ((0,2 x 0,3) x 26,0) / R

R = 0,045 m^2.K / Watt

Heat resistance P11084

The spacer knitting P11084 (Appendix 7 Spacer knitting P11084) is a spacer knitting with an open structure and a maximum attainable thickness. The results are listed in Table 11.

Table 11 P11084 measuring results

P11084	Q1= 12,1	Q2= 20,6	Q3= 41,5
T box	46,1	61,7	93,1
T inside	38,8	50,9	75,7
T outside	26,6	30,4	40,6
T ambient	20,3	20,5	21,3

For each power level a correction needs to be applied depending on the temperature difference between T box and T ambient. (ΔT) (Table 12)

Table 12 P11084 corrections

P11084	Q1	Q2	Q3
ΔT	25,8	41,2	71,8
correction [Watt]	2,5	4,0	7,0
nett heat flow [Watt]	9,6	16,6	34,5

With formula 3.8 the total heat resistance can be calculated:

Q1 = 9,6 = ((0,2 x 0,3) x 12,2) / R

R = 0,076 m^2.K / Watt

Q2 = 16,6 = ((0,2 x 0,3) x 20,5) / R

$R = 0{,}074\ m^2.K\ /\ Watt$

$Q3 = 34{,}5 = ((0{,}2 \times 0{,}3) \times 35{,}1)\ /\ R$

$R = 0{,}061\ m^2.K\ /\ Watt$

Heat resistance P11086

The spacer knitting P11086 (Appendix 8 Spacer knitting P11086) is a spacer knitting in which the spacing has been kept fairly narrow. Instead of a monofilament yarn for the distance yarn a multi filament yarn has been taken. The results are listed in Table 13 P11086 measuring results.

Table 13 P11086 measuring results

P11086	**Q1= 11,1**	**Q2= 20,7**	**Q3= 42,0**
T box	44,2	62,5	93,2
T inside	35,4	48,3	70,6
T outside	29,4	37,7	50,6
T ambient	20,6	20,9	20,8

For each power level a correction needs to be applied depending on the temperature difference between T box and T ambient. (ΔT) (Table 14)

Table 14 P11086 corrections

P11086	**Q1**	**Q2**	**Q3**
ΔT	23,6	41,6	72,4
correction [Watt]	2,3	4,0	7,0
nett heat flow [Watt]	8,8	16,7	35,0

With formula 3.8 the total heat resistance can be calculated:

Q1 = 8,8 = ((0,2 x 0,3) x 6,0) / R

R = 0,041 m^2.K / Watt

Q2 = 16,7 = ((0,2 x 0,3) x 10,7) / R

R = 0,038 m^2.K / Watt

Q3 = 35,0 = ((0,2 x 0,3) x 20,0) / R

R = 0,034 m^2.K / Watt

Heat resistance P11670

The spacer knitting P11670 (Appendix 9 Spacer knitting P11670) is characterized due to the fact that it contains elastomer. As a result an extremely closed fabric image is created. The results are listed in Table 15.

Table 15 P11670 measuring results

P11670	Q1= 12,2	Q2= 22,3	Q3= 41,5
T box	46,3	69,9	98,8
T inside	40,0	59,7	83,7
T outside	29,1	36,8	46,4
T ambient	20,5	20,8	21,7

For each power level a correction needs to be applied depending on the temperature difference between T box and T ambient. (ΔT) (Table 16)

Table 16 P11670 corrections

P11670	**Q1**	**Q2**	**Q3**
ΔT	25,8	49,1	77,1
correction [Watt]	2,5	4,8	7,5
nett heat flow [Watt]	9,7	17,5	34,0

With formula 3.8 the total heat resistance can be calculated:

$Q1 = 9,7 = ((0,2 \times 0,3) \times 10,9) / R$

$R = 0,067\ m^2.K / Watt$

$Q2 = 17,5 = ((0,2 \times 0,3) \times 22,9) / R$

$R = 0,079\ m^2.K / Watt$

$Q3 = 34,0 = ((0,2 \times 0,3) \times 37,3) / R$

$R = 0,066\ m^2.K / Watt$

Heat resistance P11680

The spacer knitting P11680 (Appendix 10 Spacer knitting P11680) resembles P11086 but has been provided with elastomer. As a result an extremely closed fabric image is created. The results are listed in Table 17

Table 17 P11680 measuring results

P11680	Q1= 11,5	Q2= 19,8	Q3= 41,6
T box	47,2	62,5	96,6
T inside	39,4	51,4	78,9
T outside	31,2	37,4	47,2
T ambient	21,2	21,2	21,2

For each power level a correction needs to be applied depending on the temperature difference between T box and T ambient. (ΔT) (Table 18)

Table 18 P11680 corrections

P11680	Q1	Q2	Q3
ΔT	26,0	41,3	75,4
correction [Watt]	2,5	4,0	7,3
nett heat flow [Watt]	9,0	15,8	34,3

With formula 3.8 the total heat resistance can be calculated:

Q1 = 9,0 = ((0,2 x 0,3) x 8,2) / R

R = 0,055 m^2.K / Watt

Q2 = 15,8 = ((0,2 x 0,3) x 14,0) / R

R = 0,053 m^2.K / Watt

Q3 = 34,3 = ((0,2 x 0,3) x 31,7) / R

R = 0,055 m^2.K / Watt

<u>Heat resistance P304671</u>

The spacer knitting P304671 (Appendix 11 Spacer knitting P304671) is a spacer knitting on which both sides have been provided with a yarn containing a cotton/polyester mixture, and elastomer. The results are listed in Table 19.

Table 19 P304671 measuring results

P304671	Q1= 11,8	Q2= 23,0	Q3= 41,3
T box	45,7	67,0	95,7
T inside	38,7	55,4	78,3
T outside	28,2	35,3	46,4
T ambient	19,4	19,6	19,8

For each power level a correction needs to be applied depending on the temperature difference between T box and T ambient. (ΔT) (Table 20)

Table 20 P304671 corrections

P304671	Q1	Q2	Q3
ΔT	26,3	47,4	75,9

correction [Watt]	2,6	4,6	7,4
nett heat flow [Watt]	9,2	18,4	33,9

With formula 3.8 the total heat resistance can be calculated:

Q1 = 9,2 = ((0,2 x 0,3) x 10,5) / R

R = 0,068 m^2.K / Watt

Q2 = 18,4 = ((0,2 x 0,3) x 20,1) / R

R = 0,066 m^2.K / Watt

Q3 = 33,9 = ((0,2 x 0,3) x 31,9) / R

R = 0,056 m^2.K / Watt

Maximum temperature of the hot box

Conform the NEN-EN ISO 8990 the maximum acceptable temperature for the hot box has been set on 40 °C. R3 is the heat resistance at a temperature >90 °C. In Table 21 it has been calculated what the deviation of R3 is compared to the average of R1, R2 and R3.

Table 21 Deviation hot box at high temperature

	10070	10086	11081	11084	11086	11670	11680	304671
R1	0,055	0,089	0,046	0,076	0,041	0,067	0,055	0,068
R2	0,060	0,077	0,051	0,074	0,038	0,079	0,053	0,066
R3	0,052	0,067	0,045	0,061	0,034	0,066	0,055	0,056
mean	0,056	0,078	0,047	0,070	0,038	0,071	0,054	0,063
deviation (%)	7	14	5	13	10	7	-1	12

Relation between stitch density and thickness

In chapter 2.3.3 it is described how Munden with the aid of the introduction of a constant factor could find a relationship between stitch length and stitch density. With regard to this there has also been a search in this study for a relationship between the different variables with the aid of the introduction of a constant factor so that a linear association with the heat resistance could be proven. The variables that will most probably exert an influence are the thickness of the spacer knitting, the stitch density and the yarn number.

The following formula has been established experimentally:

$R_{experimental}$= (thickness x stitch density) / (600 x yarn thickness) (6.1)

The results are listed in Table 22.

Table 22 Heat resistance calculated with formula 6.1

	10070	10086	11081	11084	11086	11670	11680	304671
thick-ness	2,36	4,72	2,38	4,18	1,58	3,56	2,36	3,06
stitch densi-ty	1221	1440	1254	840	1364	2590	2184	1855
yarn (dTex)	84	167	84	110	84	84	84	195
R calcu-lated	0,057	0,068	0,059	0,053	0,043	0,183	0,102	0,049
R mean	0,056	0,078	0,047	0,070	0,038	0,071	0,054	0,063

7. Conclusion

The purpose of this study is investigating what impact variables like yarn type and thickness have on the thermal resistance of spacer knitting with the aid of a test model to be newly developed. The choice was developing and building a measuring method conform NEN-EN-ISO 8990. During the first measurements measurement errors arose due to poor heat distribution in the test box. By applying the necessary adjustments this has been set straight. After calibration the test box actually turned out to have a fairly large heat loss. However, this loss of heat appeared to be linear within the applied temperature range and was incorporated in the calculations as a correction factor.

In order to be able to calculate the heat resistance, a stationary state should be reached. This cannot immediately be read with the implemented temperature sensors. With the aid of a computer this has been constantly calculated, assuming that the stationary state has been reached if the temperature has not risen more than 0.1 % compared to the average temperature during the last 20 minutes prior thereto. The calculations indicate that this assumption is correct, the calculations concerning the heat resistance do not deviate more than 0.1 % from what is considered acceptable.

As has been indicated in the NEN-EN-ISO 8990 standard, the temperature should not rise more than 40 degrees. During measurements the highest temperatures were > 90°C. On 4 qualities (Table 21 Deviation hot box at high temperature) the heat resistance deviates more than 10% at the highest temperature measured. It seems that this measuring method, as has already been indicated in the ISO standard, is not fit for higher temperatures (> 40 °C).

There is no apparent, direct relationship demonstrable between the heat resistance and the thickness of the spacer knitting. Neither has any direct relationship between the stitch density and the heat resistance been found. However, experimentally a constant factor has been calculated in combination with stitch density, thickness and yarn thickness whose results are shown in Table 22 Heat resistance calculated with formula 6.1. It turns out that in 6 different spacer knittings with the aid of formula 6.1 the heat resistance can be calculated. The spacer knittings in which this formula could not be applied was the quality P11670 and P11680. This spacer knitting is a knitted fabric of which one side consist elastan. The higher stitch density as a result of the elastan might possibly be the cause of the fact that a deviating value has been found. In that case a new constant would have to be calculated for this type of material.

8. Recommendations for future research

The designed and built hotbox appears to give a reasonable indication concerning the heat resistance in the lower temperature range. In case of higher temperatures the heat resistances deviate more than the average value in lower temperatures. However, the measured heat loss of the hotbox is linear up to about 90 °C. An explanation for the fact that the deviation is still greater could be that the measuring sensors do no longer measure the temperature accurately. A comparative measurement should be carried out with an other type of temperature gauge, for this purpose an IR temperature meter could be an option.

It has become evident that there is a relation between a number of variables of the spacer knittings and the heat resistance. Oriented research should be conducted in which the variables are chosen in such a way that the heat resistance will distinctly increase or decrease. For instance one could think of allowing the stitch density to increase in equal steps, in combination with 3 different thicknesses of the spacer knittings. Changing the yarn thickness is also recommendable here. In addition to this, it should be investigated whether an other constant applies for each base material.

When choosing the design, the hotbox was also chosen in order to be able to conduct measurements while spacer knitting is subjected to airflows. It is evident that a spacer knitting should not be chosen for its insulating capacity. For this purpose cheaper and better materials are available.

In particular the thicker spacer knittings (warp knittings) are currently implemented in mattresses and car seats because of the ventilating effect.

This investigation had to be restricted to weft spacer knittings, such since warp knittings were not available in the Netherlands.

Above studies should provide more insight into the reliability of being able to calculate the ventilating and thermal properties in the design phase for a wider range of spacer knittings in both warp and weft knitting technique. As a new application in the construction industry the thermal and breathability of spacer knittings are particularly interesting.

The air permeability is an interesting property that should allow for a closer study. With the help of the hotbox developed in this research it should be possible to measure the impact of airflows. In doing so, it would be most interesting to examine how, from the inside out, airflows of the spacer knittings can have an impact on the environment.

9 Bibliography

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10 Appendix

Appendix 1 Relation between run-in and course spacing

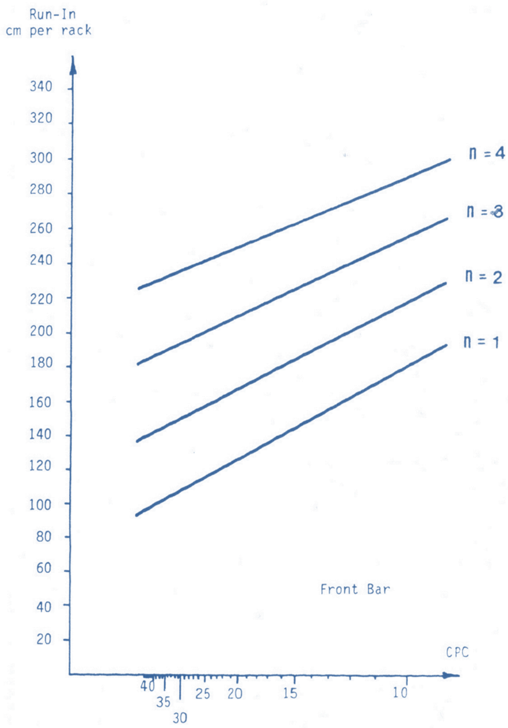


Figure 45 Front guide bar (Raz, 1987)

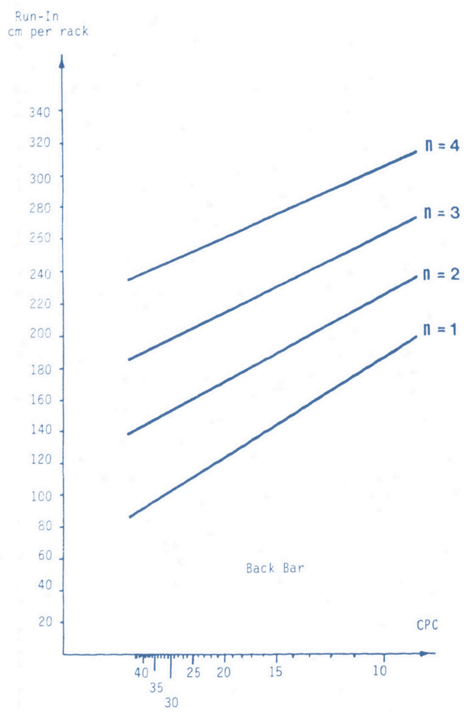


Figure 46 Back guide bar (Raz, 1987)

Appendix 2 EN ISO 8990

NEN-EN-ISO 8990:1997 en

INTERNATIONAL STANDARD

ISO 8990

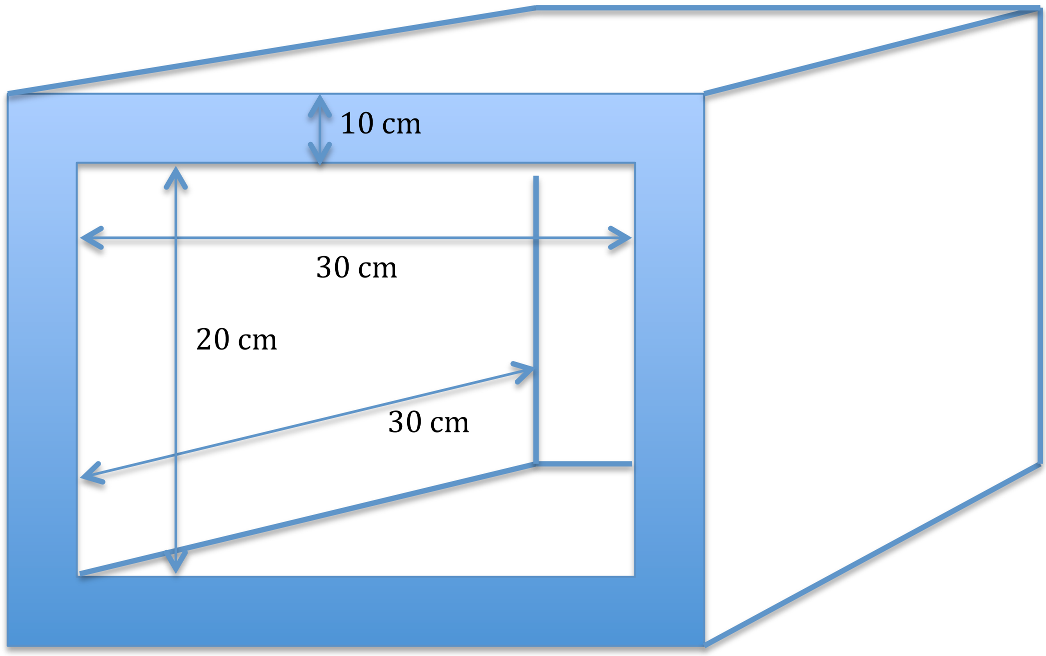
First edition
1994-09-01

Thermal insulation — Determination of steady-state thermal transmission properties — Calibrated and guarded hot box

Isolation thermique — Détermination des propriétés de transmission thermique en régime stationnaire — Méthodes à la boîte chaude gardée et calibrée

Reference number
ISO 8990:1994(E)

Appendix 3 Design of the hot box



Appendix 4 Spacer knitting P10070

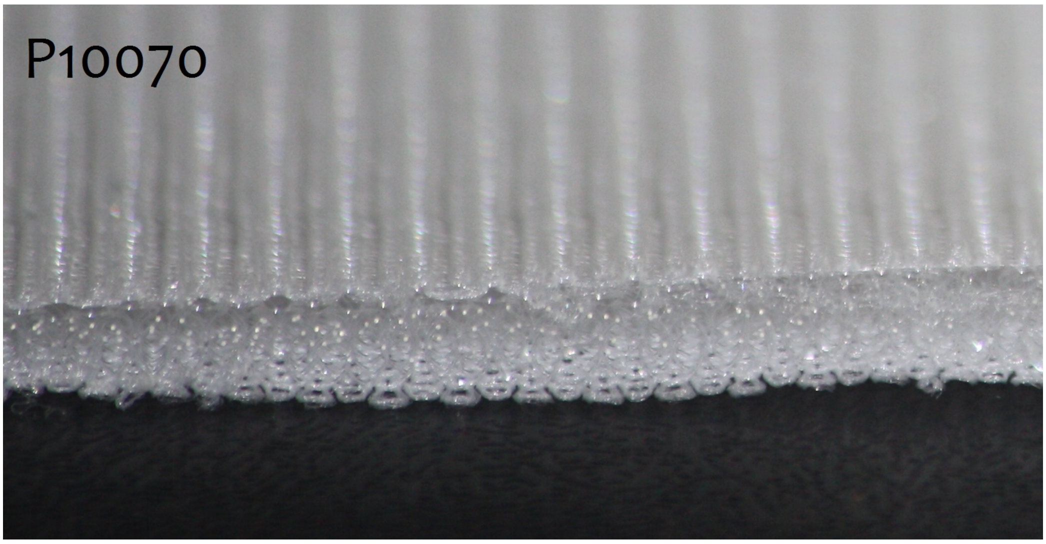


Figure 47 Photo spacer knitting P10070

Table 23 Product specification P10070

Specifications	units	value	standard
P10070	construction	weft knitted spacer fabric	
Width	cm	158	
Weight	g/m^2	185	ISO 3801
Thickness	mm	2,36	ISO 5084
Courses (3 cm)		33	
Wales (3 cm)		37	
Compression stress CV_{40}	kPa	24	ISO 3386-1
Gauge	ndl/inch	20	

Diameter	inch	30	
Yarn 1 number	dTex	84	
Yarn 2 number	dTex	88	
Yarn 3 number	dTex	84	
Raw material 1		Pes	
Raw material 2	monofilament	Pes	
Raw material 3		Pes	
Total stitch length 1	m	4.40	
Total stitch length 2	m	7.45	
Total stitch length 3	m	4.40	

Figure 48 Test results P10070 11,2 Watt

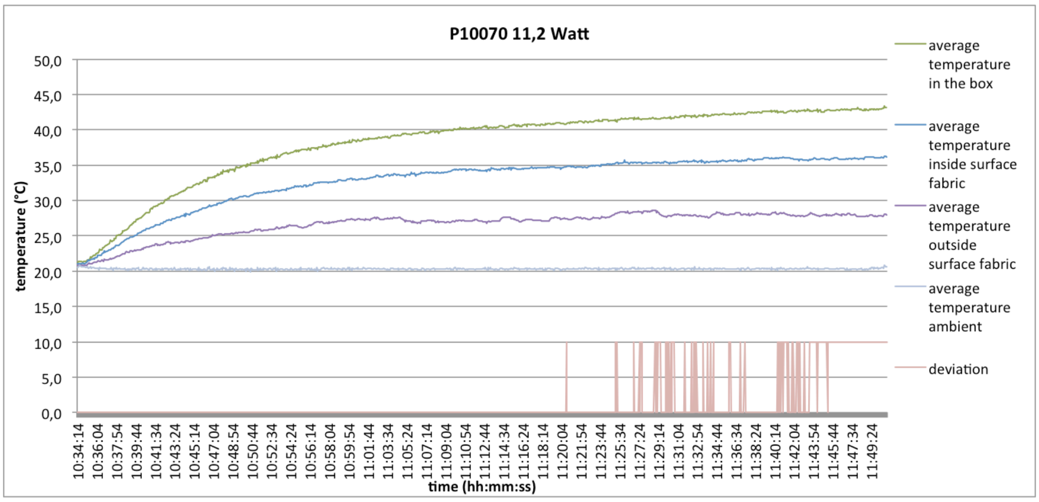


Figure 49 Test results P10070 20,8 Watt

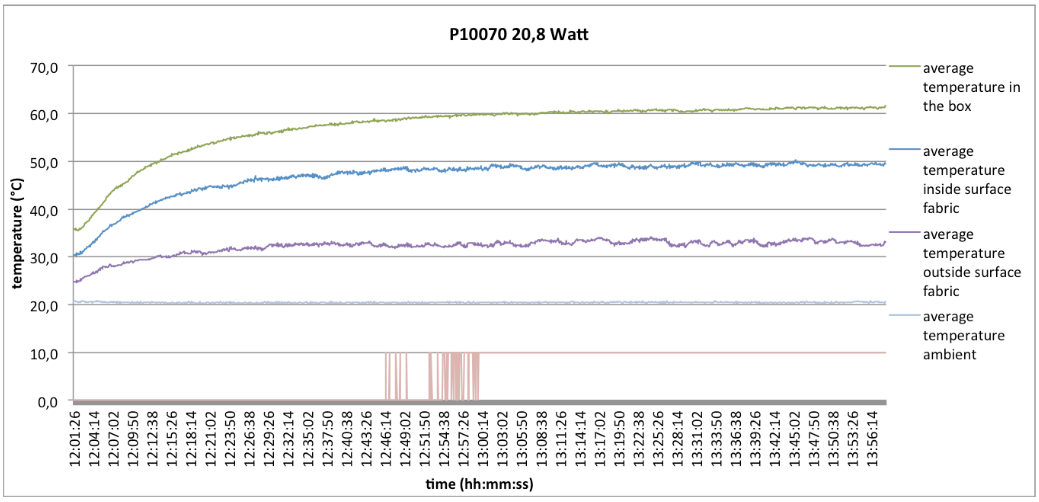
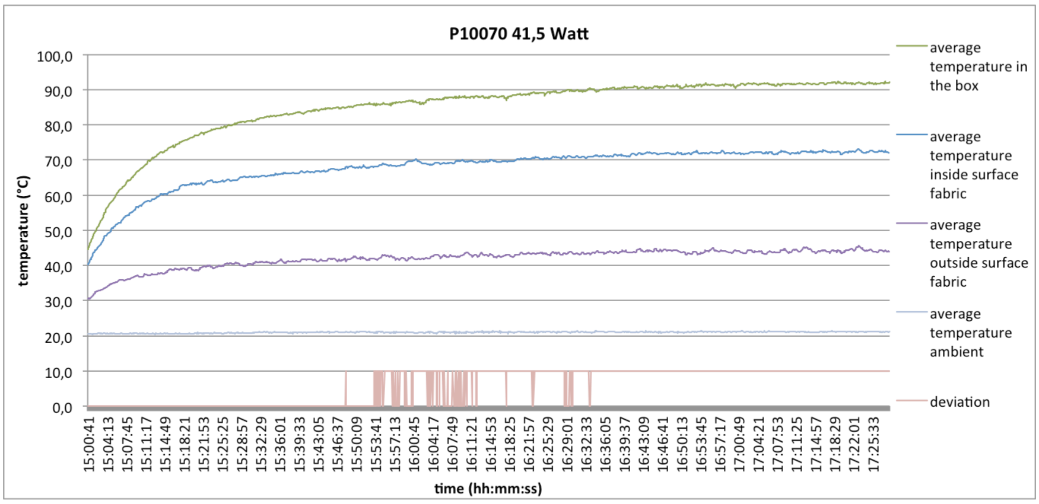


Figure 50 Test results P10070 41,5 Watt



Appendix 5 Spacer knitting P10086

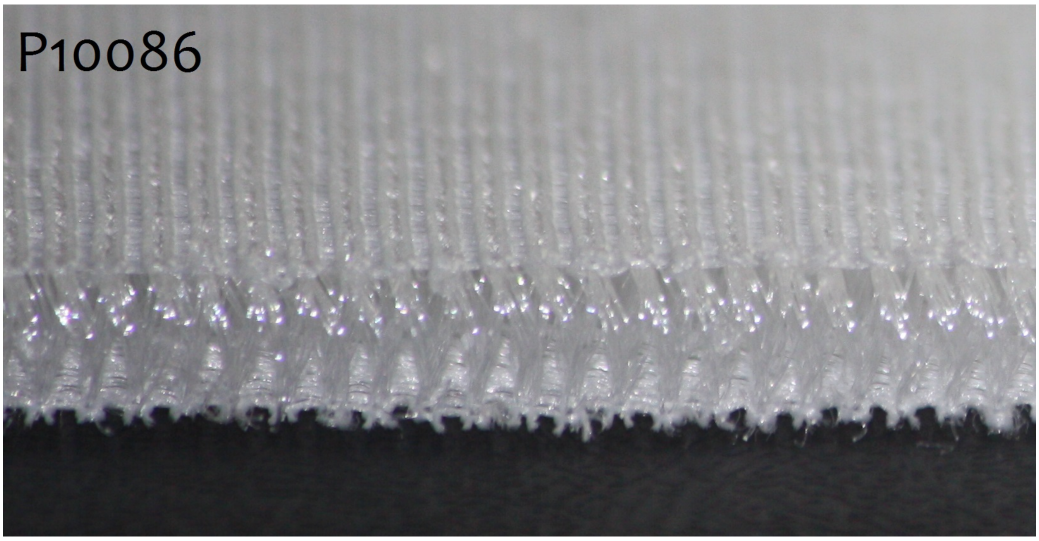


Figure 51 Photo spacer knitting P10086

Table 24 Product specification P10070

Specifications	units	value	standard
P10086	construction	weft knitted spacer fabric	
Width	cm	160	
Weight	g/m^2	404	ISO 3801
Thickness	mm	4.72	ISO 5084
Courses (3 cm)		60	
Wales (3 cm)		24	
Compression stress CV_{40}	kPa	25	ISO 3386-1
Gauge	ndl/inch	20	

Diameter	inch	30	
Yarn 1 number	dTex	167	
Yarn 2 number	dTex	88	
Yarn 3 number	dTex	167	
Raw material 1		Pes	
Raw material 2	monofilament	Pes	
Raw material 3		Pes	
Total stitch length 1	m	4.20	
Total stitch length 2	m	19.10	
Total stitch length 3	m	4.20	

Figure 52 Test results P10086 12,0 Watt

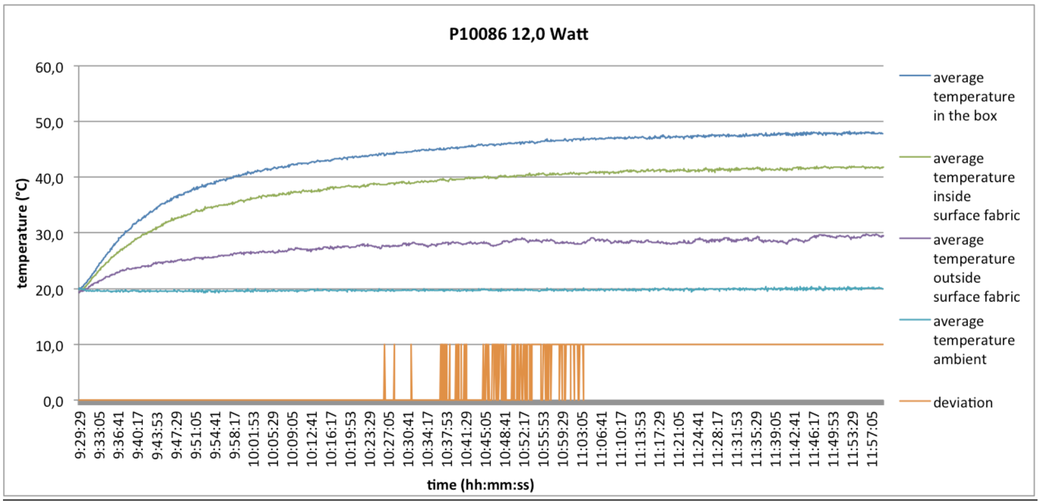


Figure 53 Test results P10086 20,9 Watt

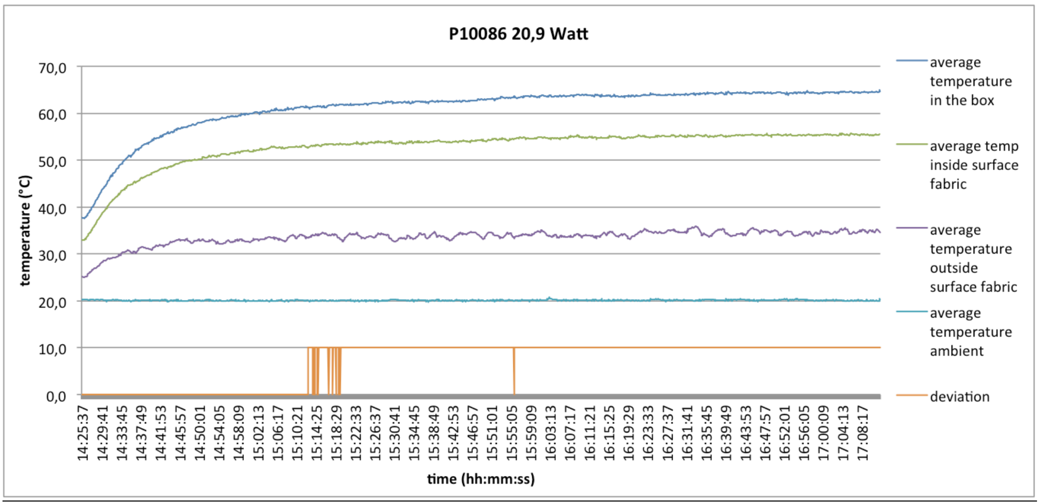
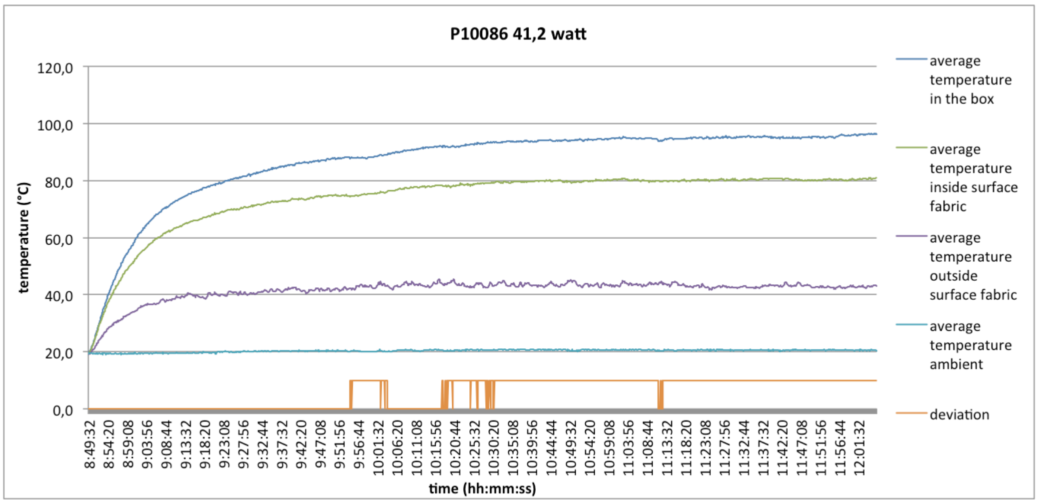


Figure 54 Test results P10086 41,2 Watt



Appendix 6 Spacer knitting P11081

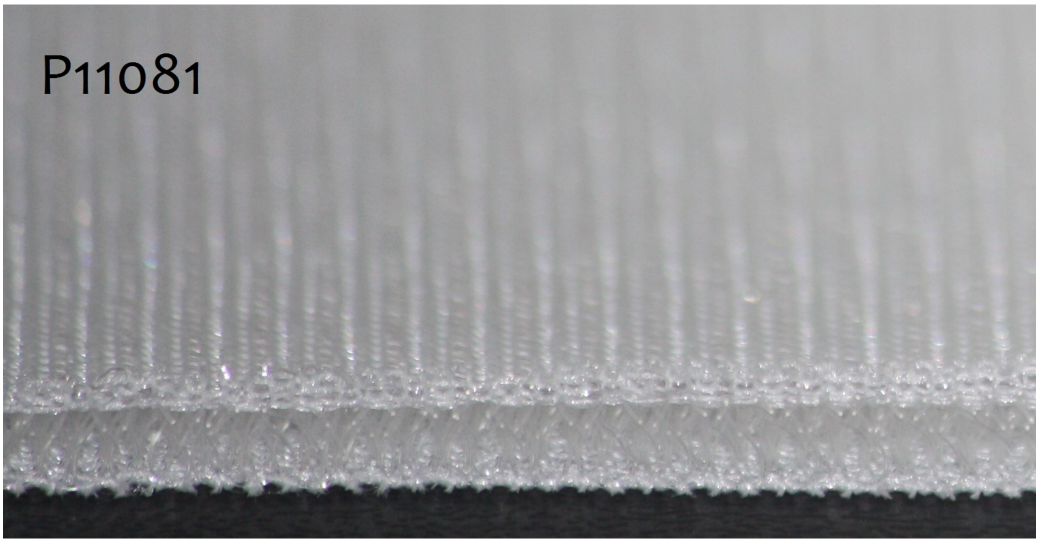


Figure 55 Photo spacer knitting P11081

Table 25 Product specification P110812

Specifications	units	value	standard
P11081	construction	weft knitted spacer fabric	
Width	cm	165	
Weight	g/m^2	268	ISO 3801
Thickness	mm	2,38	ISO 5084
Courses (3 cm)		38	
Wales (3 cm)		33	
Compression stress CV_{40}	kPa	10	ISO 3386-1
Gauge	ndl/inch	20	

Diameter	inch	30	
Yarn 1 number	dTex	84	
Yarn 2 number	dTex	88	
Yarn 3 number	dTex	84	
Raw material 1		Pes	
Raw material 2	monofilament	Pes	
Raw material 3		Pes	
Total stitch length 1	m	3.65	
Total stitch length 2	m	9.65	
Total stitch length 3	m	5.25	

Figure 56 Test results P11081 12,1 Watt

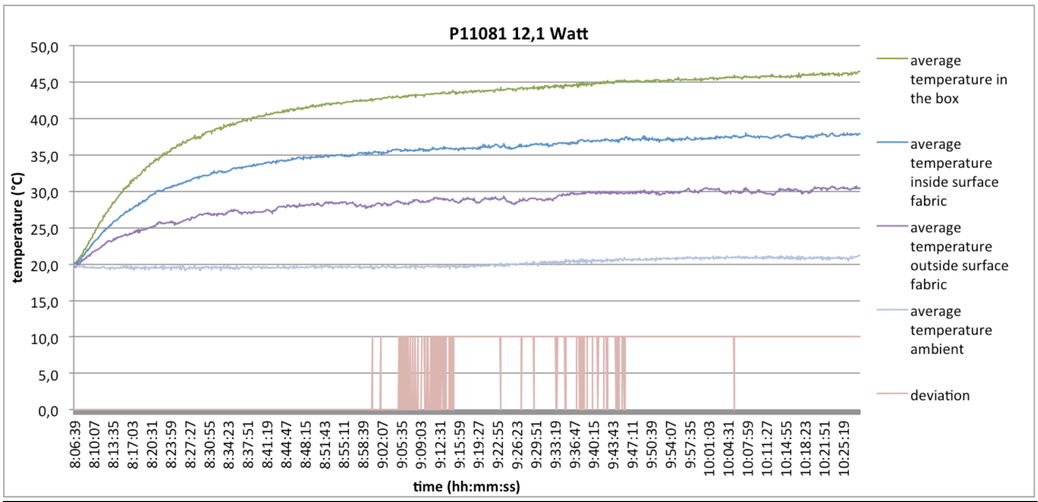


Figure 57 Test results P11081 21,3 Watt

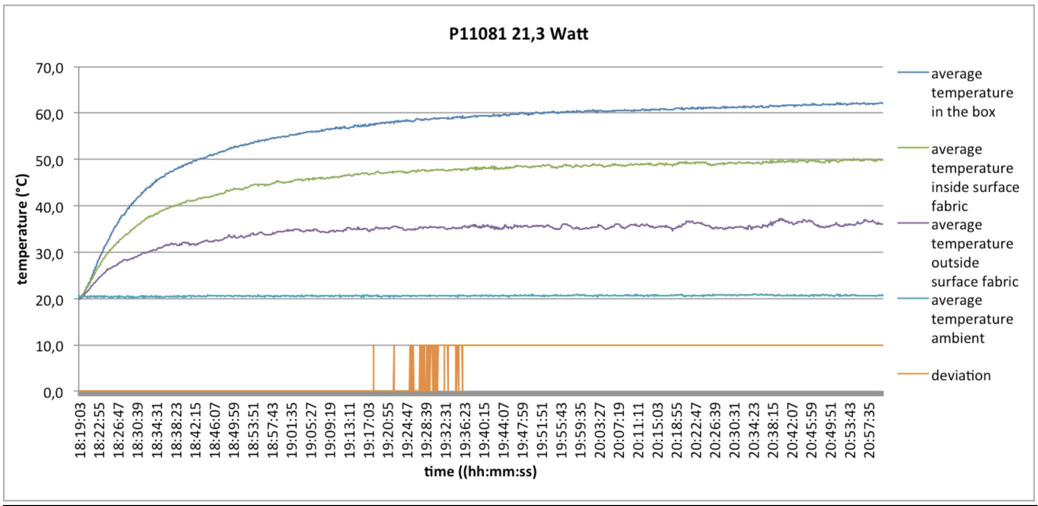
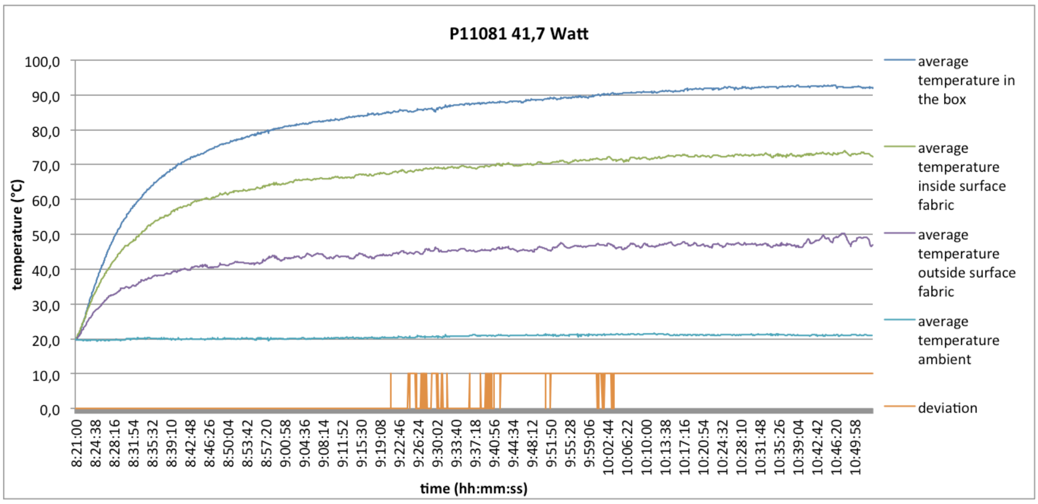


Figure 58 Test results P11081 41,7 Watt



Appendix 7 Spacer knitting P11084

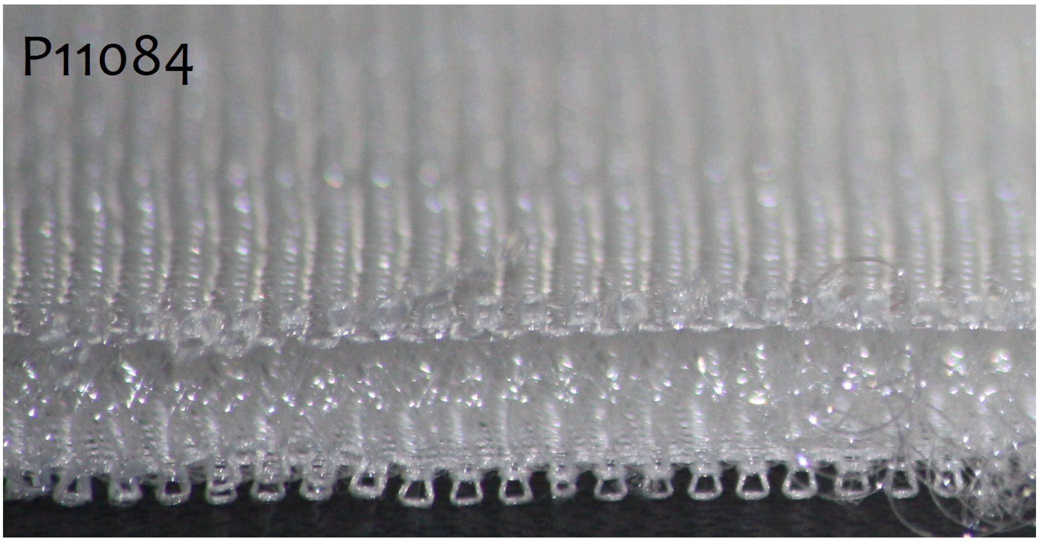


Figure 59 Photo spacer knitting P11084

Table 26 Product specification P11084

Specifications	units	value	standard
P11084	construction	weft knitted spacer fabric	
Width	cm	165	
Weight	g/m^2	229	ISO 3801
Thickness	mm	4,18	ISO 5084
Courses (3 cm)		35	
Wales (3 cm)		24	
Compression stress CV_{40}	kPa	16	ISO 3386-1
Gauge	ndl/inch	20	
Diameter	inch	30	

Yarn 1 number	dTex	110	
Yarn 2 number	dTex	88	
Yarn 3 number	dTex	110	
Raw material 1		Pes	
Raw material 2	monofilament	Pes	
Raw material 3		Pes	
Total stitch length 1	m	4.80	
Total stitch length 2	m	23.00	
Total stitch length 3	m	4.80	

Figure 60 Test results P11084 12,1 Watt

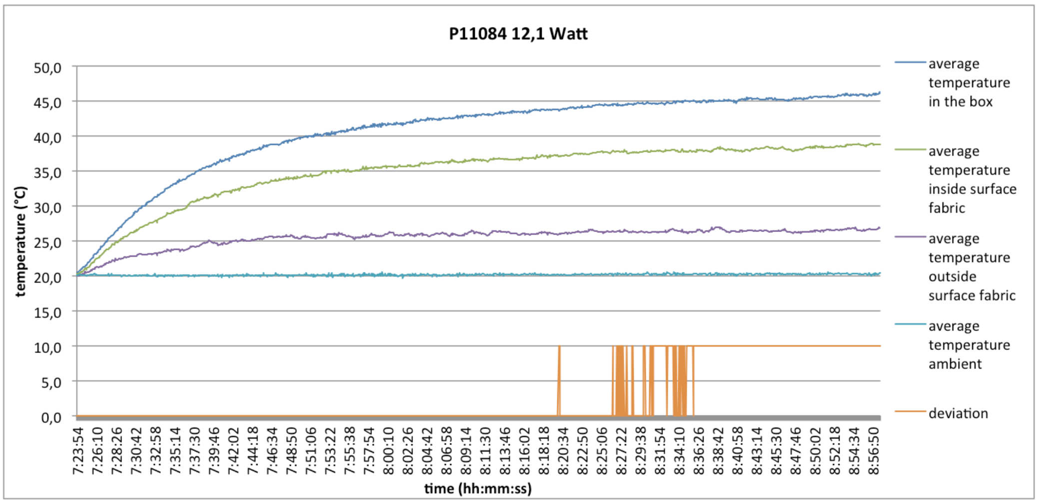


Figure 61 Test results P11084 20,6 Watt

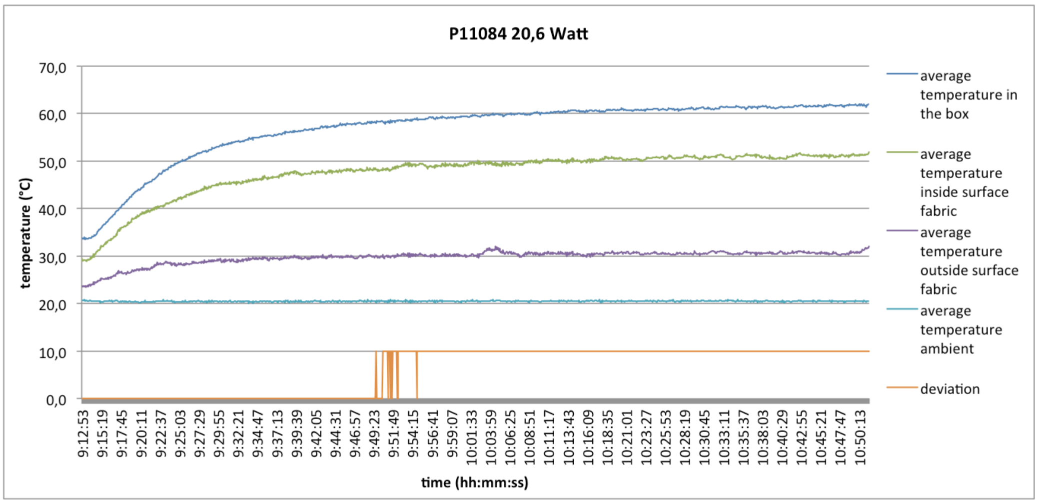
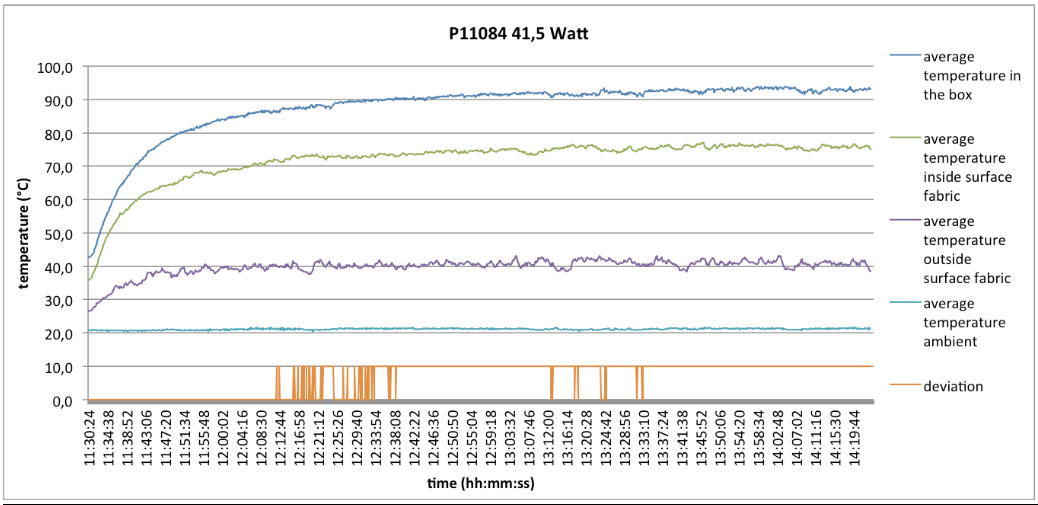


Figure 62 Test results P11084 41,5 Watt



Appendix 8 Spacer knitting P11086

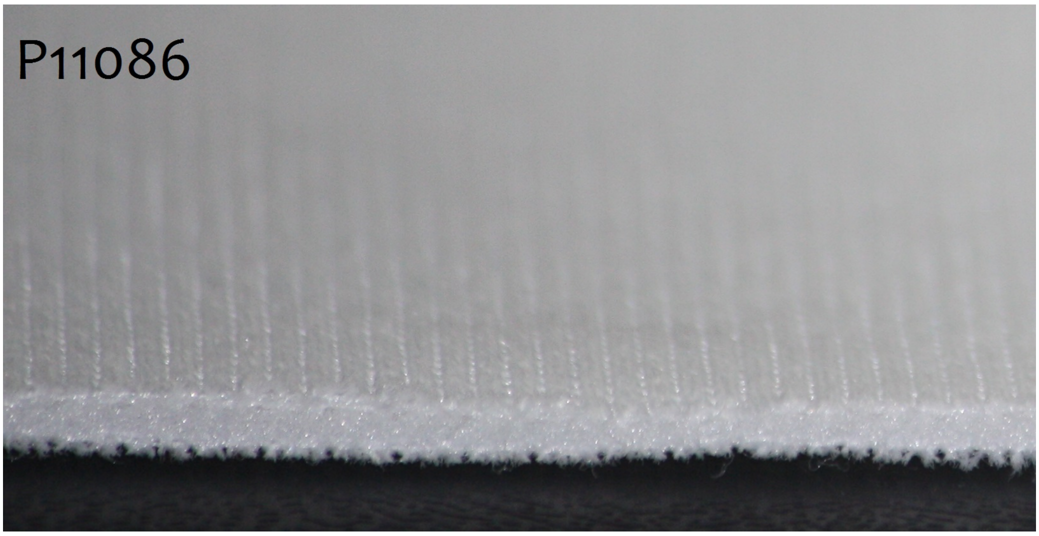


Figure 63 Photo spacer knitting P11086

Table 27 Product specification P11086

Specifications	units	value	standard
P11086	construction	weft knitted spacer fabric	
Width	cm	170	
Weight	g/m^2	238	ISO 3801
Thickness	mm	1,58	ISO 5084
Courses (3 cm)		44	
Wales (3 cm)		31	
Compression stress CV_{40}	kPa	4	ISO 3386-1
Gauge	ndl/inch	20	
Diameter	inch	30	

Yarn 1 number	dTex	84	
Yarn 2 number	dTex	84	
Yarn 3 number	dTex	84	
Raw material 1		Pes	
Raw material 2		Pes	
Raw material 3		Pes	
Total stitch length 1	m	3.90	
Total stitch length 2	m	9.40	
Total stitch length 3	m	3.90	

Figure 64 Test results P11086 11,1 Watt

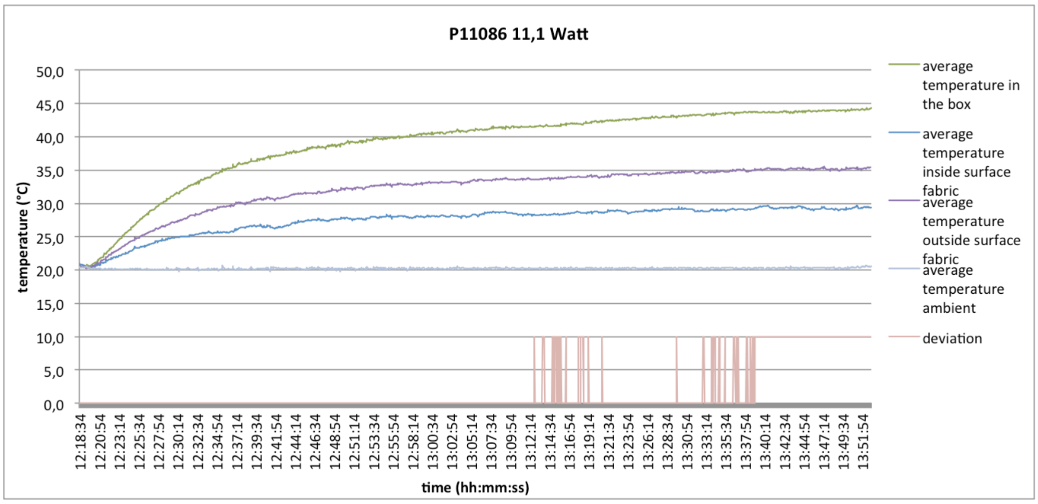


Figure 65 Test results P11086 20,7 Watt

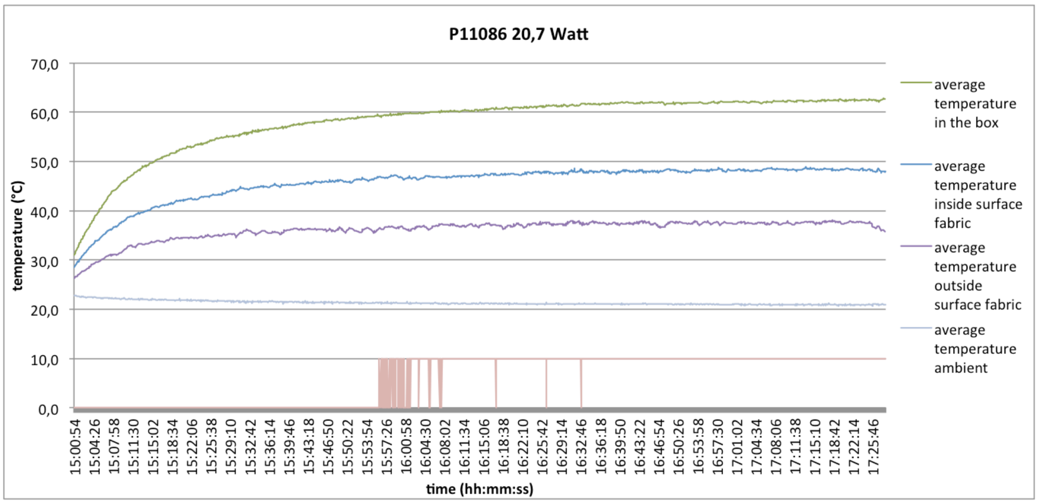
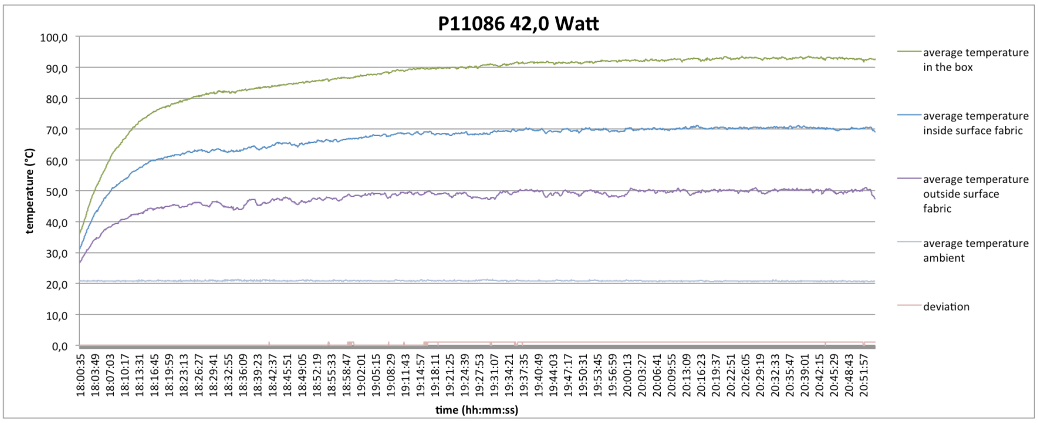


Figure 66 Test results P11086 42,0 Watt



Appendix 9 Spacer knitting P11670

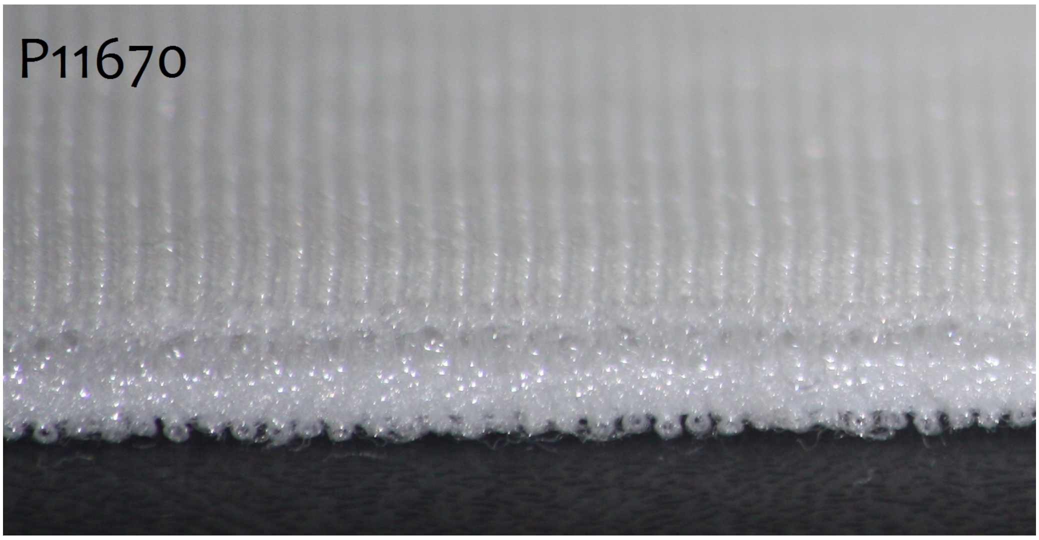


Figure 67 Photo spacer knitting P11670

Table 28 Product specification P11670

Specifications	units	value	standard
P11670	construction	weft knitted spacer fabric with elastan	
Width	cm	160	
Weight	g/m^2	458	ISO 3801
Thickness	mm	3,56	ISO 5084
Courses (3 cm)		70	
Wales (3 cm)		37	
Compression stress CV_{40}	kPa	53	ISO 3386-1
Gauge	ndl/inch	20	

Diameter	inch	30	
Yarn 1 number	dTex	84	
Yarn 2 number	dTex	88	
Yarn 3 number	dTex	84	
Yarn 4 number	dTex	22	
Raw material 1		Pes	
Raw material 2	monofilament	Pes	
Raw material 3		Pes	
Raw material 4		Elastan	
Total stitch length 1, 3	m	3.90	
Total stitch length 2	m	9.15	
Total stitch length 4	m	3.90	

Figure 68 Test results P11670 12,2 Watt

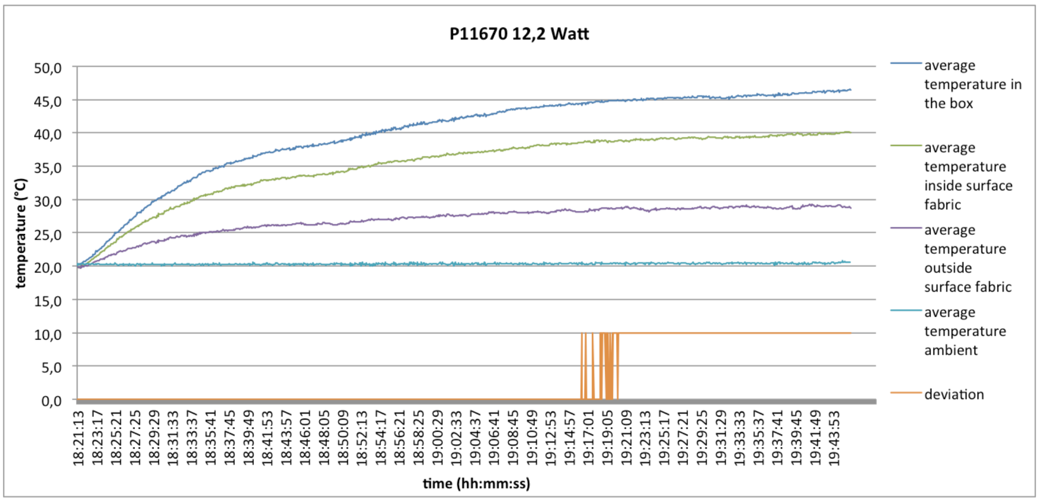


Figure 69 Test results P11670 22,3 Watt

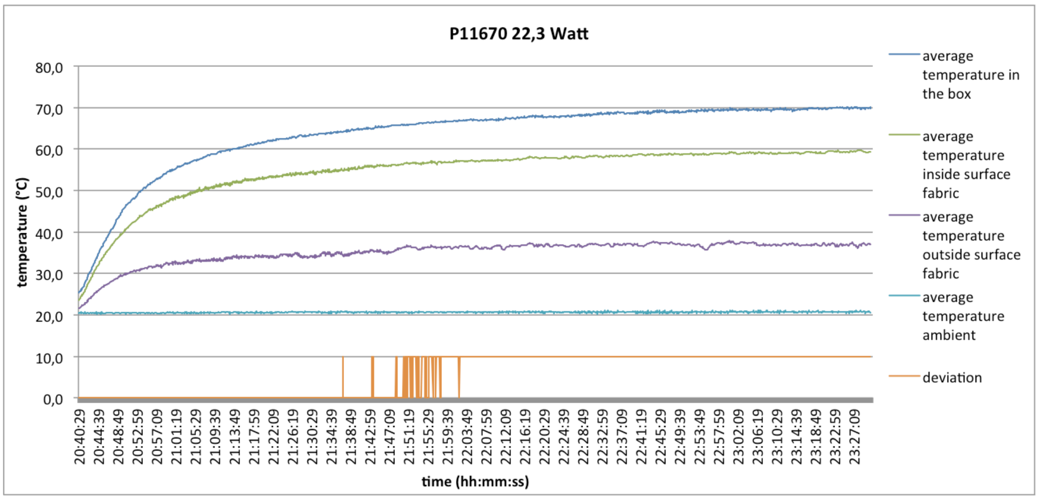
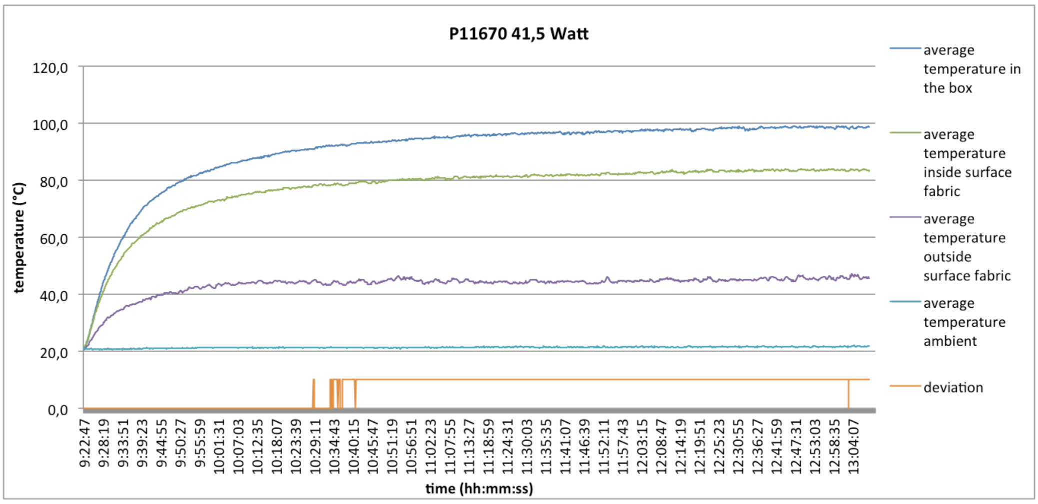


Figure 70 Test results P11670 41,5 Watt



Appendix 10 Spacer knitting P11680

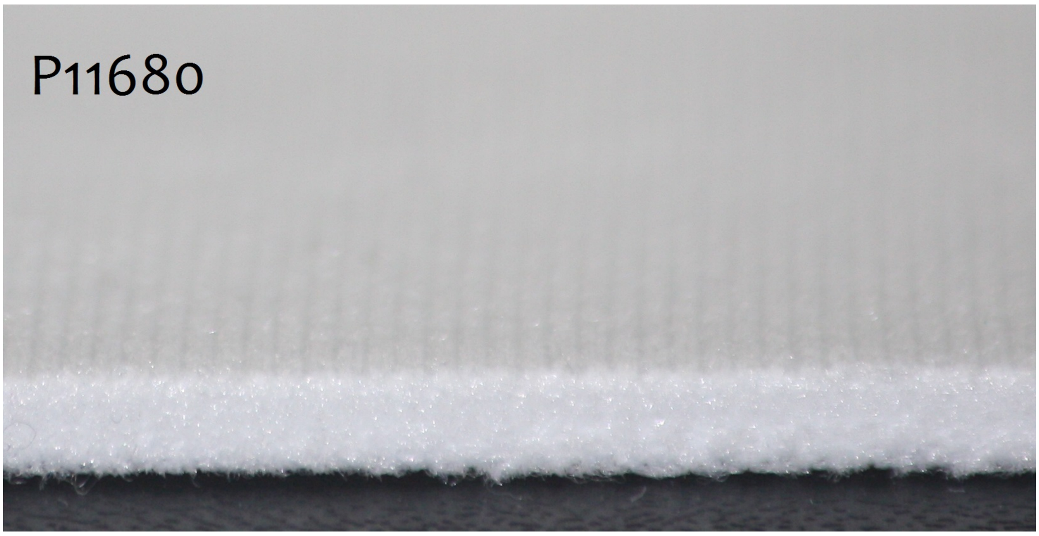


Figure 71 Photo spacer knitting P11680

Table 29 Product specification P11680

Specifications	units	value	standard
P11680	construction	weft knitted spacer fabric with elastan	
Width	cm	150	
Weight	g/m^2	379	ISO 3801
Thickness	mm	2,36	ISO 5084
Courses (3 cm)		56	
Wales (3 cm)		39	
Compression stress CV_{40}	kPa	6	ISO 3386-1
Gauge	ndl/inch	20	

Diameter	inch	30	
Yarn 1 number	dTex	84	
Yarn 2 number	dTex	84	
Yarn 3 number	dTex	84	
Yarn 4 number	dTex	22	
Raw material 1		Pes	
Raw material 2		Pes	
Raw material 3		Pes	
Raw material 4		Elastan	
Total stitch length 1	m	4.10	
Total stitch length 2	m	8.70	
Total stitch length 3	m	6.10	

Figure 72 Test results P11680 11,5 Watt

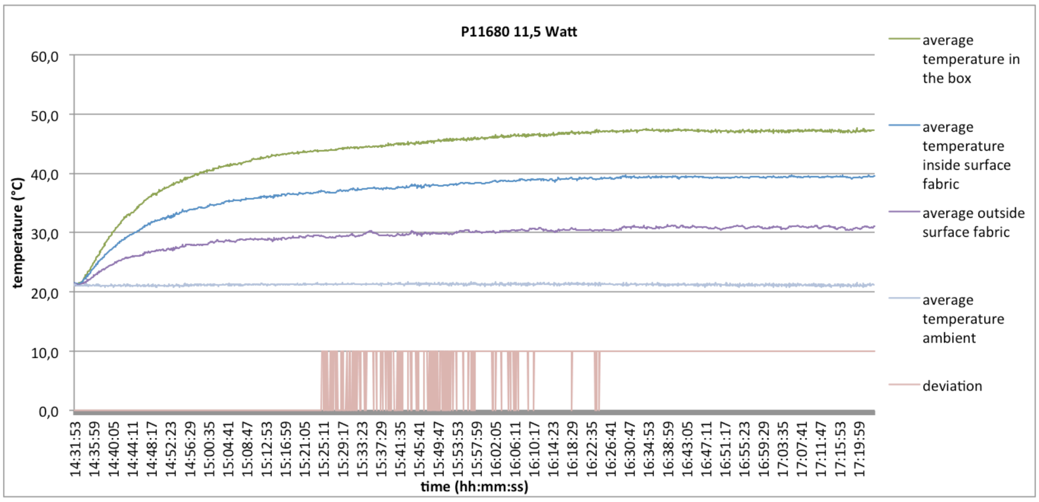


Figure 73 Test results P11680 19,8 Watt

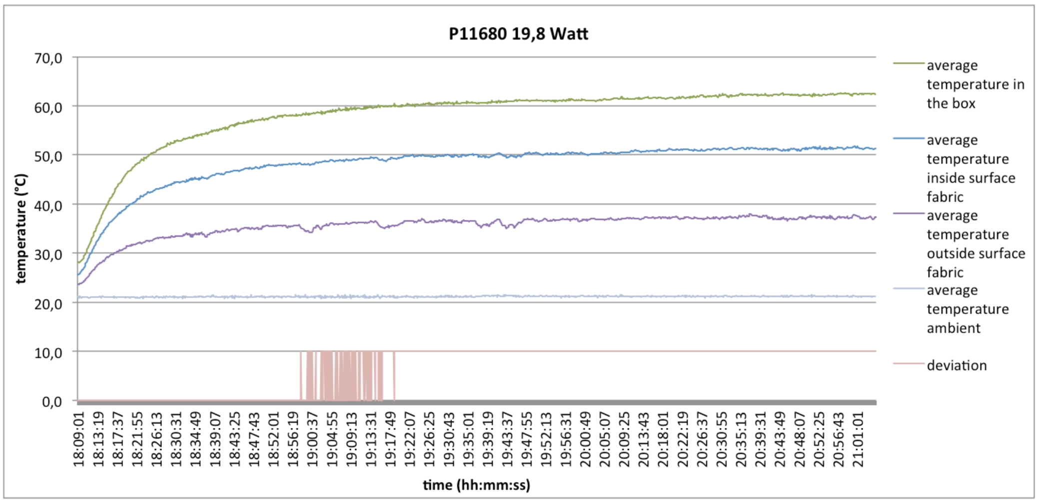
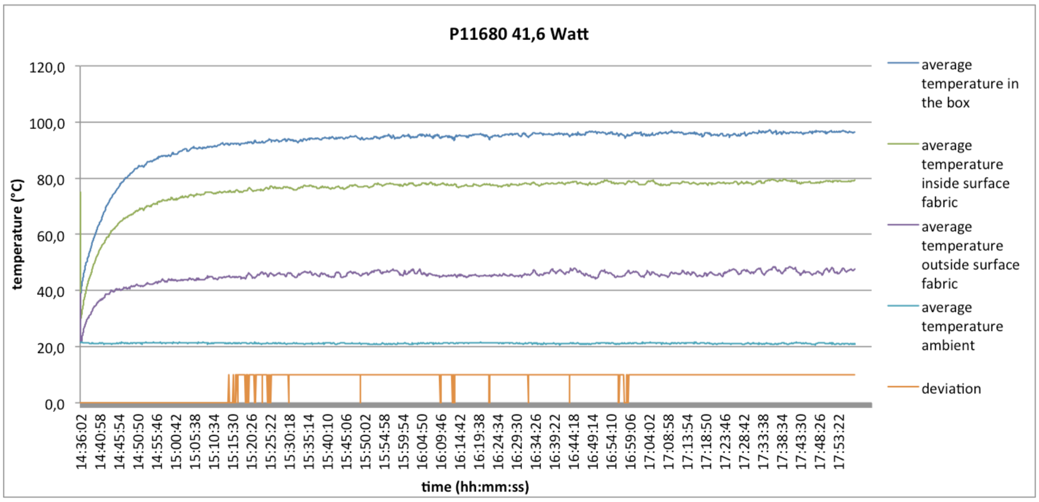


Figure 74 Test results P11680 41,6 Watt



Appendix 11 Spacer knitting P304671

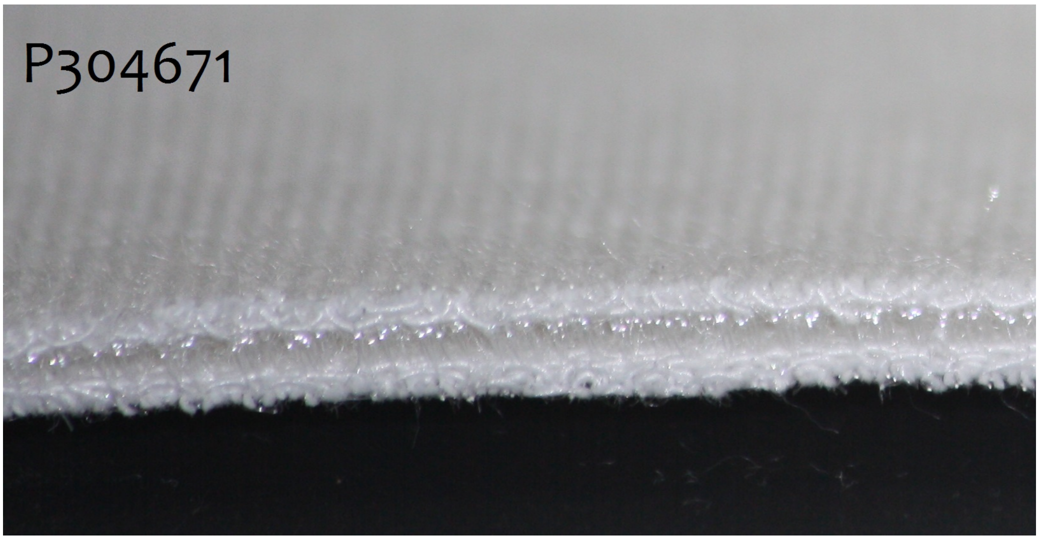


Figure 75 Photo spacer knitting P304671

Table 30 Product specification P304671

Specifications	units	value	standard
P304671	construction	weft knitted spacer fabric with elastan	
Width	cm	160	
Weight	g/m^2	470	ISO 3801
Thickness	mm	3,06	ISO 5084
Courses (3 cm)		53	
Wales (3 cm)		35	
Compression	kPa	20	ISO 3386-1

stress CV_{40}			
Gauge	ndl/inch	20	
Diameter	inch	30	
Yarn 1 number	Ne	30/1	
Yarn 2 number	dTex	88	
Yarn 3 number	Ne	30/1	
Raw material 1	65/35	Pes/Co	
Raw material 2	monofilament	Pes	
Raw material 3	65/35	Pes/Co	
Total stitch length 1	m	4.80	
Total stitch length 2	m	7.60	
Total stitch length 3	m	4.80	

Figure 76 Test results P304671 11,8 Watt

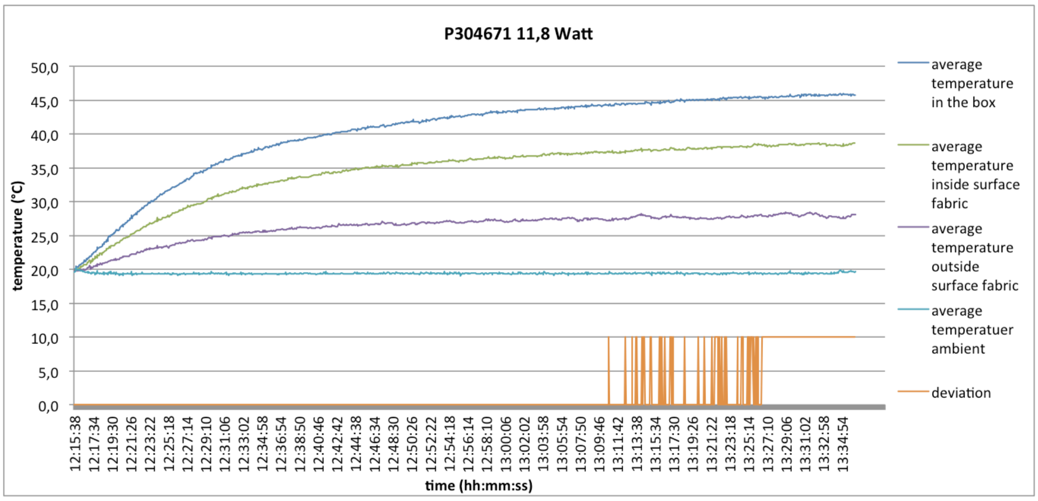


Figure 77 Test results P304671 23,0 Watt

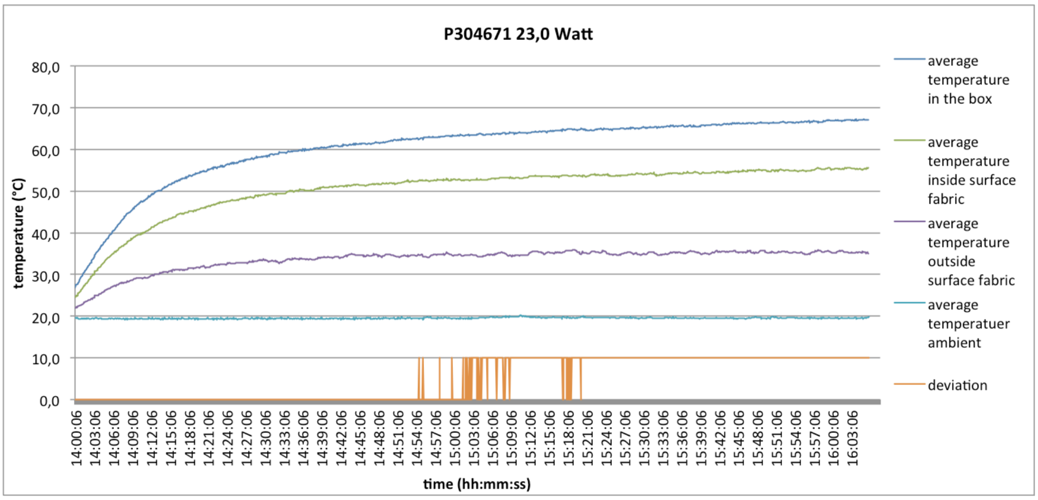


Figure 78 Test results P304671 41,3 Watt