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Estimating the Thermal Properties of Flat Products by a New Non-contact Method

Abstract
A new non-contact method dedicated to identifying the mechanisms of heat transfer through a flat sample is described. The method consists in measuring the infrared radiation emitted from both sides of a flat sample at the same time using two infrared mirrors and a thermovison camera. The temperature – time characteristics recorded are analysed and by their shape and mutual position, the existence of thermal conduction, convection and infrared radiation is identified. A measuring stand as well as standard samples of specific structure special design for the purpose of this investigation are described. The method can be used for flat samples of every kind but is especially devoted to textile applications. Temperature - time dependencies characteristic for a standard sample as well as a hemp-fibre stitched nonwoven are presented and discussed. Criteria for determining the heat transfer mechanisms are listed, and directions for further development of this method are proposed.

Key words: *temperature measurements, thermovision, infrared radiation, convection, thermal conduction, non-contact method.*

Introduction

Determination of the thermal properties of flat products is very important, especially in the case of those serving as thermal insulation. Two-dimensional textile products in the form of woven & knitted fabrics, nonwovens and complex multilayer structures play an especially important part in thermal insulation. The transmission of thermal energy through a 2-D porous structure forced by an existing temperature difference, not taking into account mass transfer, takes place by three different heat transfer mechanisms: heat conduction, convection, and infrared radiation [1 - 4]. In general, we can briefly state that heat transmission occurs by heat conduction whith according to Fourier's law is the transmission of internal thermal energy directly into the given body by direct contact between bodies, transmission by convection, which is connected with the movements of gas particles at different temperatures, and by thermal radiation, which consists of electromagnetic wave emission by a body temperature higher than the absolute zero, which also takes place in a vacuum. In the majority of cases, heat transport involves all three mechanisms, but their share is different. As opinion is popular that heat energy in textiles takes place only by conduction, this opinion is not always true.

It is very important to know by which kinds of thermal transmission the insulation considered by us is characterised, and how great the shares of the particular mechanisms are. Many contact [5 - 9] methods dedicated to estimating the properties of insulation are known. But any one of the hitherto used methods allow to determine the existence and share of conduction, convection and radiation in the total heat transfer through a sample at the same time. Therefore we initiated a cycle of investigations with the aim of developing a non-contact, non-destructive method that allows to distinguish the kinds of heat transfer through flat samples and their share in the total heat transfer [10 - 16]. We formulated a thesis that the analysis of temperature curves, with dependence on time, determined for a thermal system designed with the specific configuration of the sample, as well as a heater and non-contact measuring device will allow to identify and describe the heat transfer mechanisms governing the case analysed. The first objective of our research was to recognise samples of complex textile nonwovens, and therefore we began our investigations with an artificial model which would allow to determine their internal structure exactly.

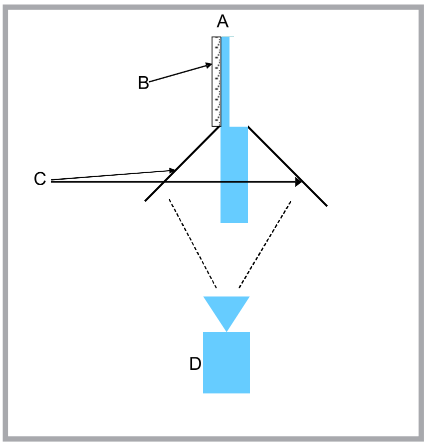

***Figure 1.** Scheme of the measuring stand; A - 2D sample, B - heater, C - two infrared mirrors, D - thermovision camera.*

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Further investigations are provided, dedicated to enlarging the possibilities of the method developed to assess the values of such quantities as thermal resistance, thermal conductivity, the heat absorption coefficient and radiation emissivity, amongst others. The aim of this article is to present the principles of the new method, the procedures used for measurements, and examples of applying the method, as well as propose ways of developing the method in the future.

Basic principles of the method

The new method is based on the interpretation of time dependency records, measured by a thermovision camera, of a temperature distribution measured at the same time by the radiation of both sides of a flat sample heated in the part which is not exposed to the IR measurement. A measuring stand was designed and built; the scheme of this stand is presented in ***Figure 1***.

Half of the sample, fastened flat on the stand, is heated on one side by a heater which is switched on by hand by a manipulator. The stream of heat goes through the sample surface layer from the heated region into the unheated one. At the same time the heat begins to flow through the thickness of the sample in the direction of the opposite surface of the unheated region. The time relations of the heat flow depends on the kind of heat transmission which takes place in the transfer. Two infrared mirrors are placed at an angle of 45° on the edge of the side covered by the heater and unheated parts of the sample. A thermovision camera is placed at the extension of the sample's edge and directed at the surfaces of both mirrors. The signal recorded by the camera is linked to a computer for further processing. In this way we can record the temperature distributions on both sides of the sample at the same time. The stand can also be used for standard measurements without mirrors, which are easy removable.

Preliminary measurements with specially prepared teflon samples

We decided that multilayer nonwovens would be the first real test materials due to their complex structure, characterised all three heat transfer mechanisms. But in order to correctly interpret the phenomenon observed, it was necessary to construct an imitation of a multilayer structure with the defined characteristics of the material layers as well as air spaces of defined dimensions and position it within the sample in which convection could occur. The material of the sample layers should be partly transparent to IR radiation, with a visible differentiated level of absorption within the sample thickness range of 0 – 10 mm. The transparency

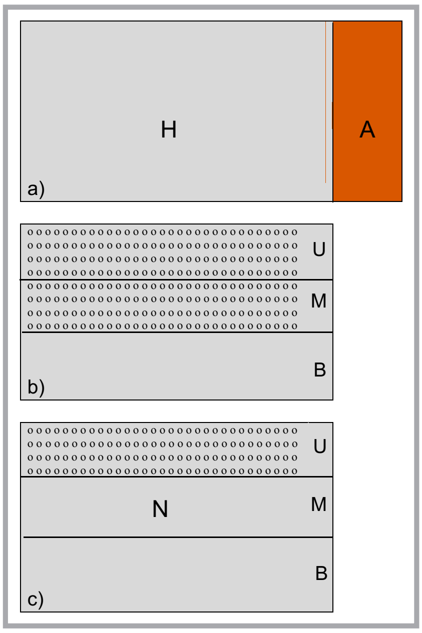

Figure 3. *Side views of the teflon plates of the test sample; a) external plate, heated (designated A, heated surface – H), b) internal, unheated perforated plate, c) external unheated plate (designated N); parts of the plates: U – upper, M – middle, B – bottom.*

of various materials were assessed with the use of the stand designed but without mirrors, which means in a standard mode. The average temperatures of a selected rectangular area of the heater and of the sample surface opposite the heater were assessed and compared. As an example the histograms together with data of the

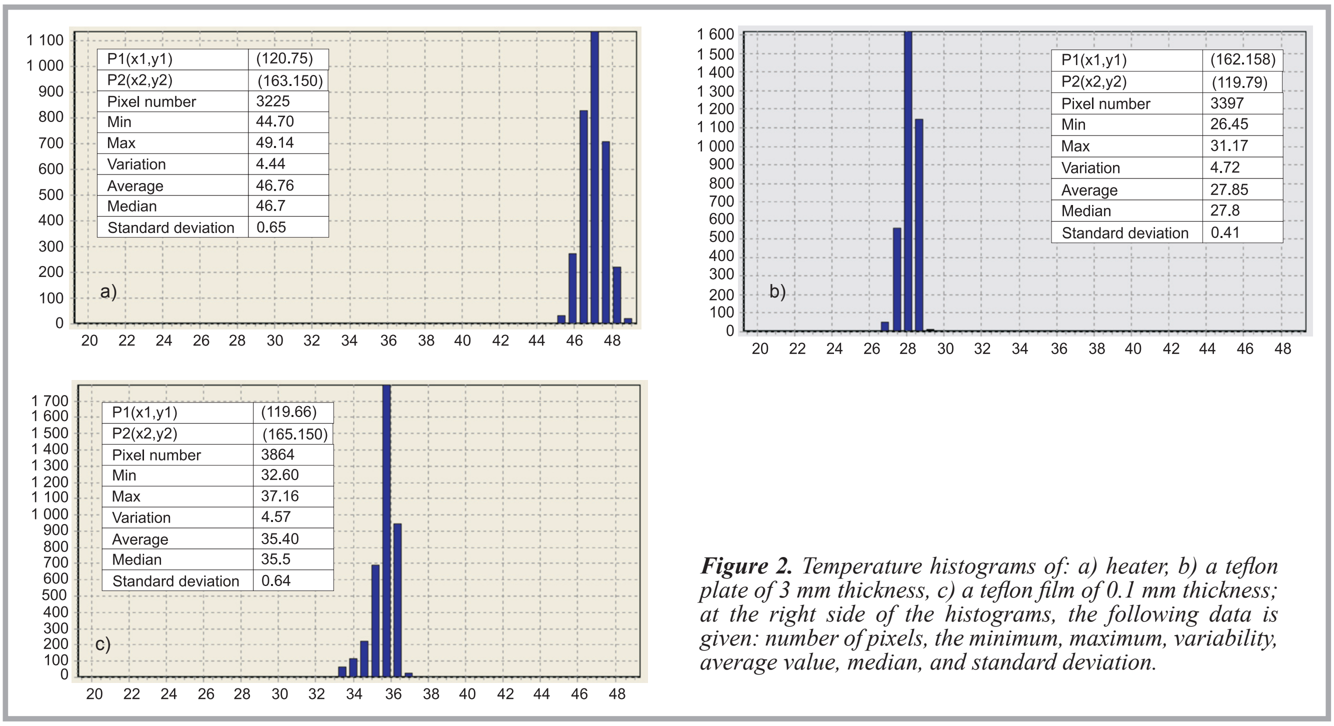

Figure 2. *Temperature histograms of: a) heater, b) a teflon plate of 3 mm thickness, c) a teflon film of 0.1 mm thickness; at the right side of the histograms, the following data is given: number of pixels, the minimum, maximum, variability, average value, median, and standard deviation.*

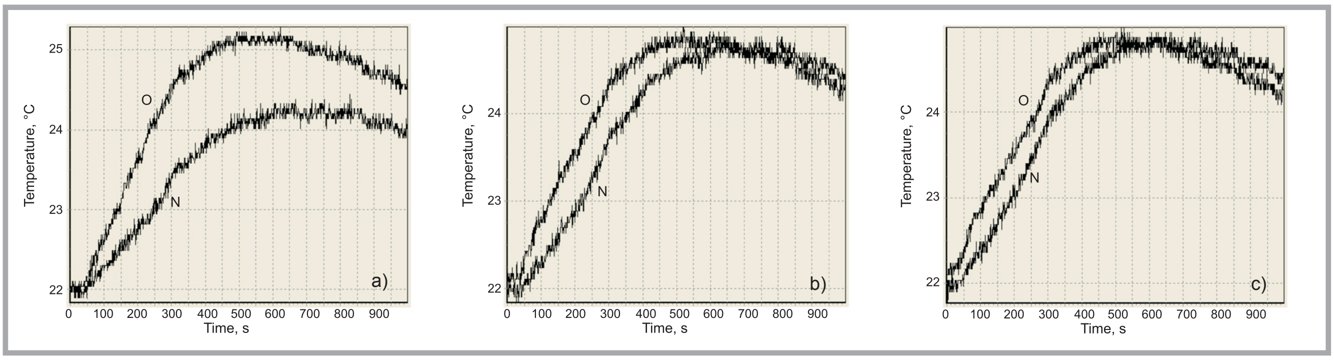

Figure 4. *Temperature – time dependencies of pairs of points positioned on the O and N sides of the plates in the following configurations: a) without a hole, b) with a hole in the middle plate, c) with two holes in the middle and second external plates, which coincide mutually.*

measurements are presented in ***Figure 2***, for the teflon finally chosen. For this material, which is partially transparent to IR radiation, at an average heater temperature of 46.8 °C, the temperature of a 0.1 mm thick film was 37.2 °C and that of a 3 mm thick plate was 27.8 °C. An additional advantage of selecting teflon was that it is easy to machininge and not degradable.

The sample was constructed from three teflon plates, each with a thickness of 3 mm and structure specially programmed by us (***Figure 3***). The plates were put together and secured from sliding. The set of plates was positioned vertically on the stand. The first heated plate was made longer in order to direct the heat flow to the opposite external plate only in the region controlled by the thermovison camera (samples made from textile materials tested later were prepared with a similar extension). The shorter internal and secondary external plates were provided with holes, playing the part of pores in a nonwoven sample for example. The plates may be divided virtually into three parts: the upper (U), the middle (M), and the bottom (B) part. Taking this into account, the holes are placed in the internal plate in the U and M zones, whereas in the external plate they are only in the U zone. The mirrors were positioned at the boundary between the heated and unheated parts of the sample. During the tests, the sample was heated for 50 seconds, and next switched off. A disadvantage of the interpretation of our primary investigations was that, after being switched off, the heater further warmed the sample due to its thermal inertia: however, with an intensity decreasing with time; which caused that the measurements were conducted in dynamic conditions. Thermograms were recorded by a thermovison camera with a frequency of 1 image per second. The total time period of recording was 1,000 seconds, which means that 1,000 images were recorded.

Although even a quick observation of the thermograms allows to identify the location of holes on the sample by their different temperatures, the places were marked on the sample in order to more precisely identify their position. The first series of measurements were carried out for pairs of points positioned on opposite sides of the sample (O – heated, and N – unheated) at various positions of the three zones: the upper, middle and bottom. In ***Figure 4*** temperature – time dependencies of the pairs of points at places without any hole, with a hole in one plate and with holes at the same position in two plates are presented. It should be emphasised that in the latter case the holes coincide mutually. The temperature of the thermograms is presented with a resolution of 0.1 °C

Analysis of the dependencies obtained allowed to indicate the following characteristic features, which are common for all the three cases analysed:

- The temperature of the heated sample surface is, in almost all cases, higher than the temperature of the opposite surface within the time period analysed.
- The temperature increase on both sides (O and N) starts at the same time.
- The temperature increase starts with a time lag of about 50 seconds in relation to the moment of switching on the heater.
- The rate of temperature increase of both sides (O and N) is greater than the rate of temporary decrease after achieving the maximum temperature.
- The temperature increase of the unheated side (N) lasts longer than that of the heated one (O).

However, essential differences in the temperature – time dependencies could be observed between the particular cases, which allowed to test the hypothesis formulated at the beginning of our investigations, concerning the possibility of identifying the particular heat transfer mechanisms. Below are listed the differences between the two groups; the first is the time periods of temperature increase, and the second is when the temperatures of sides O and N are approximately constant, and next decrease.

Time increasing period:

- While analysing the case of the sample without any hole (Figure 4.a), it is clear that the temperature - time dependencies of sides O and N have the same character; only the temperature increase of the unheated side (N) is considerably slower, which is normal for simple inertia systems with heat flow by conduction.
- In the cases of temperature – time dependencies for the pair of points positioned at one or two holes (***Figure 4.b*** and ***4.c)***, the dependency of side N differed in character from that of side O; the characteristic influence of inertia was not visible.

Period of similar temperatures (of sides O and N) and temperature decrease:

- The cooling characteristics of both sides (O and N) were similar in character.
- For a great majority of samples with holes in two plates, the temperature of the unheated surface (N) increased during the first 550 seconds, but later became approximately constant and equal to the temperature of side O, and only after 750 seconds did it begin to decrease, but with a value higher than the temperature of side O.

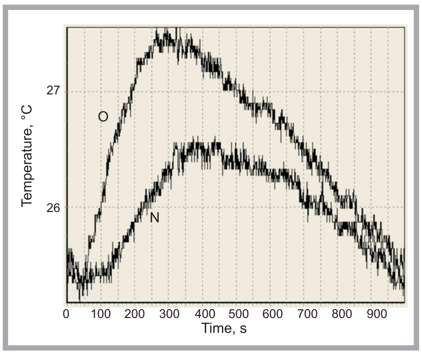

Figure 5. Temperature – time dependencies of pairs of points positioned on sides O and N of a sample with glossy aluminium foil inserted.

- For a great majority of samples with holes in the internal plate, the temperature of the unheated surface (N) increased during the first 600 seconds, but later became approximately constant and equal to the temperature of side O, and only after 850 seconds did it begin to decrease. From this moment the temperature of the unheated (N) side of the sample was higher than that of the initially heated one for the whole period of observation carried out by us.
- It can be stated that a number of samples with a hole in the internal part of the sample had similar temperature runs to those of samples without a hole, but these latter were characterised by significantly higher temperature differences between the sides O and N, and the temperature of side N was never higher than that of side O, even in the periods of temperature decrease.

A summarised analysis of the temperature – time dependencies, assuming that the runs for different positions of the holes are considered as independent samples, allows to draw the following conclusions:

- The samples consisting of plates without a hole are characterised by conductive heat transfer through the sample and additional radiation from the sample to the thermovision camera.
- In the case of samples with holes (one or two layers), which are similar in structure to textile samples with a porous structure and closed or open pores, the heat transmission takes place by conduction, convection and radiation, including mutual heat exchange between the surfaces of the holes.
- We identified that the heat transport through the sample thickness due to radiation takes place as the initial temperature increases on both of the opposite sides (O and N), which begin at the same moment, without a time lag. Furthermore, it was previously determined by us that teflon is partly transparent to IR radiation, (see ***Figure 2***, page 73).
- Identification of the presence of convection was possible on the basis of temperature – time dependencies of samples with holes. Within the spaces of the holes, air particles have the possibility to move and transport heat energy. Therefore, after reaching the maximum temperature of the surface (O), which was heated at the beginning of the test for 50 seconds, the temperature of the surface opposite to it (N) was further heated by convection, and its temperature increased beyond the actual temperature of side N. Analysing the dependencies obtained, it should be remembered that they present dynamic states, that the heater is switched off after 50 seconds of action, and that although the temperature of side N may be higher than that of side O at a particular moment, it cannot be higher than the highest temperature obtained by side O during any time period before.

In order to confirm that, for heat transport by radiation, the teflon material of the sample was responsible, the sample structure was modified. Between the external plate without holes, which was heated, and the next plate, a glossy aluminium foil was inserted. Such a foil is totally non-transparent to electromagnetic radiation of the wavelength used. The temperature – time dependencies obtained for this case are presented in ***Figure 5***.

By comparing both temperature dependencies, it is visible that the temperature of the unheated surface (N) increased with a time delay of about 75 seconds. It should be emphasised here that the

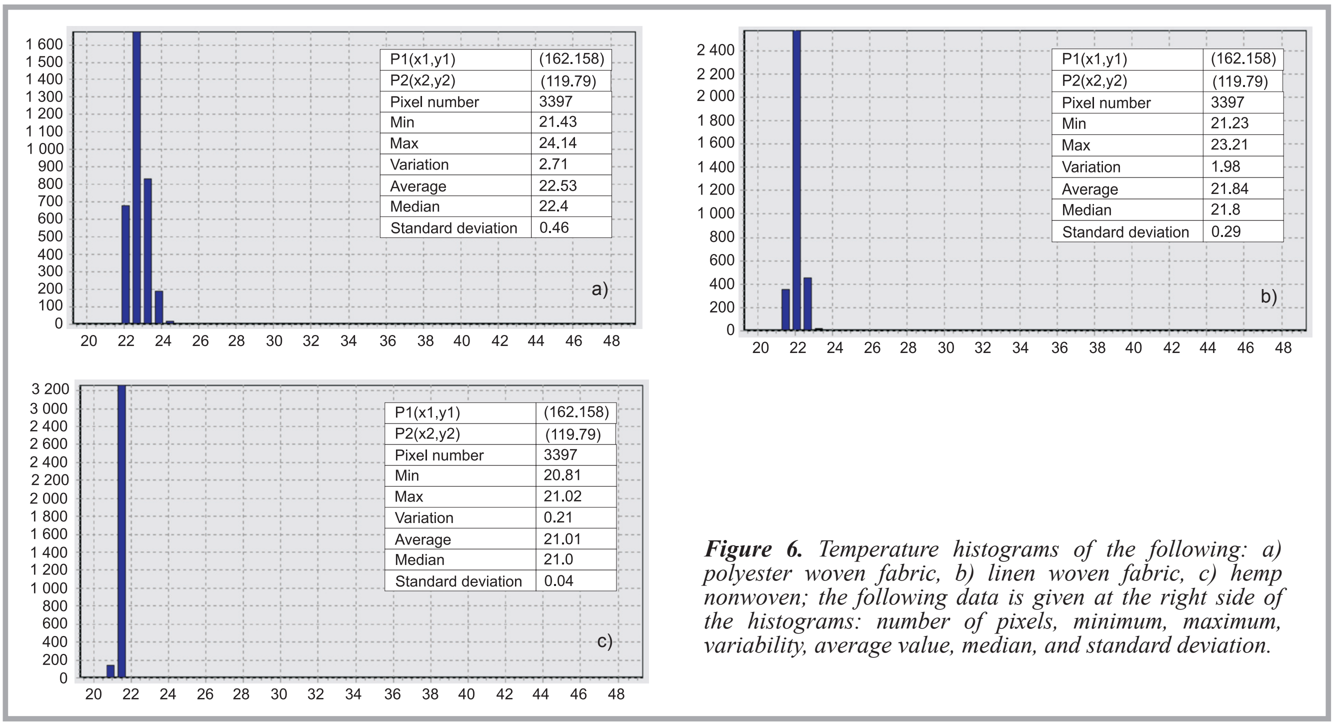

Figure 6. Temperature histograms of the following: a) polyester woven fabric, b) linen woven fabric, c) hemp nonwoven; the following data is given at the right side of the histograms: number of pixels, minimum, maximum, variability, average value, median, and standard deviation.

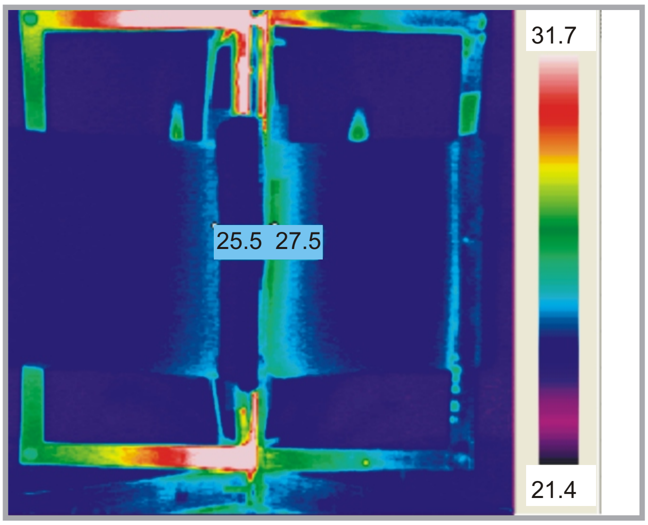

Figure 7. Thermogram of a hemp nonwoven taken after 425 second after switching on the heater (375 seconds after switching it off). The two mirrors are clearly visible.

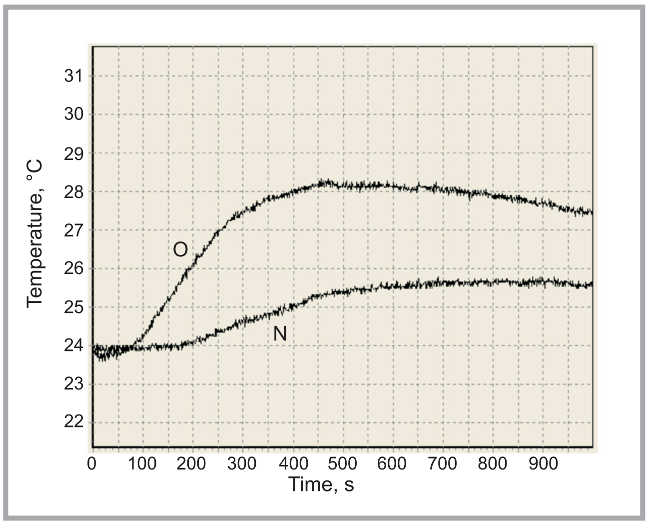

Figure 8. Temperature – time dependencies of a pair of points placed on the heated (O) and unheated (N) side of a hemp nonwoven sample.

temperature and time conditions of heating the sample, as well as the position of the selected pair of measuring points along the sample, were different as in the cases presented in ***Figure 4***, which resulted in a difference in the maximum temperature obtained for both sides (O and N) as well as in the time of their occurrence. The experiment presented confirmed the possibility of identifying the presence of radiation in heat transfer by analysing the first period of the temperature increase of both sides of the sample tested.

Additionally, on the basis of analysing the temperature – time dependencies obtained, we can assume that in the future it will also be possible to determine some thermal properties of the samples tested, for example the thermal conductivity of the sample material. In order to determine the values, which we would determine, we must describe the heat flow with appropriate equations, and from the temperature differences, temperature gradients and time delays of the higher (O) and lower (N) temperature curves for a selected part of the sample, we can calculate the quantity.

Measurements with textile samples

Determination of the transparency to IR radiation is a relatively simple measurement (it should be considered only as preliminary identification of the materials used in samples) that is carried out with the use of the measuring stand, used in this investigation but without mirrors, which means in a traditional mode. ***Figure 6*** (see page 75) presents histograms of three textile materials measured with the same heater characteristic, which is presented in ***Figure 2.a*** (see page 73), and with which the histograms of the teflon plate and film were carried out (***Figure 2.b*** and ***Figure 2.c***). Linen and polyester woven fabrics and a hemp nonwoven were selected as textile samples. The average temperature of the polyester fabric was equal to 2.5 °C, the linen fabric – equal to 21.8 °C, and the hemp nonwoven – equal to 21.0 °C. The standard deviations for all three cases were 0.04 °C in in comparison with 0.84 °C for the teflon plate. The hemp nonwoven appeared to have the smallest transparency.

Below, there is described an example of the application of the method developed by us to determine the heat flow mechanisms of a textile sample. A hemp nonwoven was chosen as the subject of our investigation, taking into account that hemp has a relatively small transparency to IR radiation. Hemp fibres with an average linear density of 41 dtex, (CV of 27%), and average length of 38.3 mm (CV of 30%) were used for manufacturing the nonwoven by one-side stitching. The nonwoven was stitched at a constant depth of 12 mm and with a number of stitches of 120 per cm^2 using 15×18×40×3.5 RB needles. This technological process was chosen in order to obtain a porous structure. The finished nonwoven was characterised by an area mass of 330 g/m^2, apparent density of 0.0042 g/cm^3, air permeability of 471.9 dm^3/m^2s, and working thickness of 9.8 mm.

Heating was performed similar to that used in the preliminary measurements. Recording was conducted with a frequency of two images per second over a period of 500 s. This, as well as data processing, was performed with the use of a Thermoscope software program, which eliminated errors connected with reading the values measured. A thermogram recorded at the 425 second from the start of heating the sample, is shown in ***Figure 7***. The temperature – time dependencies of a selected pair of points situated on opposite sides of the sample is presented in ***Figure 8***. Several time dependencies for the same as well as for different pairs of points were carried out with similar results.The runs presented in ***Figure 8*** are a good, characteristic example of the results obtained.

The initial temperatures of the sample were 23.8 °C for side O and 24.0 °C for side N. The temperature of the unheated side (N) starts its increase with a distinctive time lag of about 83 seconds, which confirm the small transparency of the sample to IR radiation. The temperature increase of side O lasted to the 225th second from switching on the heater, and next a slow decrease began. The temperature of side N increased to the 300th second, was approximately constant to the 425th second, and only then did it begin to decrease, albeit very slowly. The maximum temperature of side O was 28.2 °C, whereas it was 25.7 °C for side N. The rates of temperature increase in similar straight linear parts of the characteristics were 0.09 °C/s and 0.06509 °C/s respectively. The abovementioned observations indicate that, irrespective of the lack of transparency to IR radiation, the heat is transported through the sample with a distinctive share of convection in the total heat transport, which indicates the porous structure of the sample tested.

Conclusions

- The hypothesis of the possibility of estimation of the mechanisms of heat transfer through a flat sample, which means determining the share of conduction, convection and radiation, formulated by the authors was verified.
- The verification of the hypothesis was carried out with the use of specifically designed standard samples of determined structure made from a single, selected material, as well as with textile samples specially prepared.
- It was indicated that by the non-contact method, with the use of two mirrors and the thermovison camera developed by us, on the basis of temperature – time dependencies of the heated and non-heated sides of the sample, it is possible to identify the particular heat transport mechanisms.
- The method developed by us allows broad extended investigation of thermal processes proceeding with time across the sample thickness and along the sample.
- The results obtained allow to predict that a possibility exists of determining the values of the thermal parameters of the samples tested, for example those of thermal conductivity
- Research into further developing the method presented herein should be undertaken.

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