2003 BELTWIDE COTTON CONFERENCES, NASHVILLE, TN – JANUARY 6-10

# THERMAL CONDUCTIVITY OF NONWOVENS MADE OF NATURAL FIBERS

**Oldrich Jirsak and Klara Kalinova**
**Technical University of Liberec**
**Liberec, CZ**

## Abstract

With respect to heat transfer, fibrous assemblies must be treated as a special case of porous media. Over that, the textiles of hygroscopic fibers containing absorbed water and placed in a temperature gradient are porous media with a phase change. Absorbed water evaporates in the region with higher temperature consuming energy. The vapor then diffuses toward the lower temperature region and condenses again. Thus, an additional heat transfer mechanism occurs in hygroscopic textiles. The contribution of this mechanism to the total heat transport is quantitatively studied and conclusions with respect to thermal insulating properties are formulated.

## Introduction

The mechanism of heat transfer in dry textiles has been studied and described in detail [Caps and Umbach, Farnworth, Stark and Fricke]. In wet textiles, an additional heat transfer mechanism occurs besides the conduction and the radiation [Fan, Luo and Li, Muraba]. Condensed water, whether liquid or absorbed in hygroscopic fibers, evaporates close to the hot surface of textile material consuming heat. Water vapor then moves toward the cold surface by the free convection and diffusion. In the cold part of a textile layer, the vapor condensates again producing condensation and/or sorption heat.

It is easy to understand this additional heat transfer mechanism, nevertheless it is difficult to calculate its contribution to the total heat flow. The contribution depends on a number of variables such as the amount of water in fibrous materials, temperatures of both the surfaces, water and the vapor permeability of surfaces, the vertical or horizontal position of surfaces etc. Moreover, when dealing with hygroscopic natural fibers, it is not easy to quantify the sorption and desorption energy of water in the fiber material. There is a variety of bonds and corresponding bond energies for absorbed molecules of water depending on the fiber hygroscopicity and structure, amount of water etc. [Pierlot].

The water, after having been transported and condensed close to the cold plate can be moved back towards the hot plate by the capillary mechanism and/or gravity if the arrangement of the system is suitable. Then, the contribution to the heat transport by the phase change mechanism would be extremely significant.

Excellent theoretical and experimental work has been done to describe simultaneous heat and water transport in fibrous materials [Fan, Luo and Li, Muraba]. Besides that, the influence of water on thermal insulating properties can be directly evaluated in specific boundary conditions provided a suitable measuring device is available. The device must show a reasonably short time response.

The influence of a small quantity of water on thermal conductivity of textiles has been studied. The amount of water in the materials was controlled by conditioning at specific values of relative humidity.

## Experimental

Thermal conductivity of needle punched textiles made of polyethyleneterephtalate, wool and cotton fibers was evaluated using a device consisting of a hot and cold plate and a heat flux sensor [7]. Effective thermal conductivity $\lambda$ and its development in time was measured .The textiles were conditioned before measurement in specific states:

1. Heat dried at 105 C, 2 hours
2. Conditioned at 47 % relative humidity and 20 – 22 C for 48 hours
3. Conditioned at 95 % relative humidity and 20 – 22 C for 48 hours.

Relative humidities of 47 and 95 % were obtained in closed vessels over saturated solutions of KSCN and $Na_2SO_3$ respectively.

Thermal conductivity of samples was measured between an upper hot (35 C) and a lower cold (25 C) plate of the device in two different situations. Some measurements were carried out between a lower hot (35 C) and upper cold (25 C) plate to asses the possible influence of gravity on the backward transport of condensed water. The samples were measured in following situations:

1. Inserted in a polyethylene bag immediately after conditioning. The surplus air was removed out of bag by a slight compression and the bag was closed by welding.
2. Without the bag

## Textile Materials

The textiles were produced by carding – cross layering – needlepunching process.
Needlepunching: Needles No. 36 NKU, 70 punches/cm$^2$, needle depth penetration 11 mm.
Area weight of samples: 67 g/m$^2$, thickness ca. 4 mm.

Fiber materials:

A. PET – polyethyleneterephtalate, 6.7 dtex, 65 mm
B. Wool – Scoured Australian wool, length 57 – 70 mm, fineness 60/64's,
C. Cotton – Mechanically cleaned Egyptian cotton GIZA 77, type 7730/32,Length 37 mm, fineness 3.4 Mic

## Measurement Procedure

Temperature of plates: Cold – 25 C, Hot – 35 C

Distance between plates: 10 mm

Laboratory climate: Temperature 20 – 22 C, Relative humidity 45 – 47 %.

Procedure: Three layers of the sample were conditioned as per 1., 2. or 3. (see above). Then the sample was placed inside the polyethylene bag (measurement situation I.) or directly between the plates of measuring device.

Note: The dried sample (conditioning mode 1.) was allowed to cool down 15 minutes before measurement, either in the bag or over dry silicagel in an exsiccator. The samples were slightly compressed between the plates as the original thickness of layered sample exceeded 10 mm. Thus, the density of the samples during measurement was 20 kg/m$^3$.

After placing the sample between the plates, recording of heat flow was started. Simultaneously, the data of a differential thermocouple (diameter 0.08 mm) placed on both cold and hot plates were recorded to check up the exact difference in temperatures of the plates. The measurement was terminated after the value of effective thermal conductivity became constant.

Arrangement of measuring device: The heat flux sensor was placed on the lower plate. The lower plate was the cold one in most of experiments (Fig. 1-6, 9) as it is usual is conductivity measurements. In additional experiments (Fig. 7 and 8), the results obtained in lower cold - upper hot arrangement were compared with those in lower hot - upper cold set up to judge possible influence of gravity and/or capillary transport of condensed water.

## Results

The time development of measured thermal conductivity of materials is shown in Figures 1 – 6. The materials had been conditioned at 0 %, 47 % and 95 % of relative humidity before the measurement. The results shown in Figures 1, 3 and 5 were obtained for the samples placed in a plastic bag, the results in Figures 2, 4 and 6 without the bags. Important experimental data are in Table I.

Cotton and woolen fabrics, conditioned at 95 % relative humidity were measured inside plastic bags between the lower cold - upper hot plates and lower hot - upper cold plates, respectively. The results are compared in Fig. 7 and 8.

The energy $Q_x$ consumed by the wet samples was calculated by integrating the heat flow vs. time curve shown in Fig. 9 and called surplus heat. The $Q_x$ values are compared with total evaporating energy of water contained in conditioned samples in Table II.

## Discussion of Results

The graphs in Figures 1 -6 show the time development of effective thermal conductivity. After the conditioned sample has been placed between cold and hot plate of measuring device in time zero, some time is required for establishing a constant temperature gradient through the material. Three to five minutes time is a typical time of this stage if the thickness of samples is 10 mm. After a constant gradient has been reached, all the dry samples show a constant and almost the same value of effective thermal conductivity (see Table I.). The same is true for non-hygroscopic polyester material whether being conditioned at the low or high relative humidity and measured inside a plastic bag or free. Hygroscopic materials - wool and cotton - conditioned at the high value of relative humidity, contain a certain amount of bound water (see water regain in Table I.). Their effective thermal conductivity grows for some time and then falls towards a constant value close to that plastic bag of a dry material. This was found for the samples measured in a plastic bag as well as without it. In the plastic bag, condensed water can be seen close to the cold plate. Despite the presence of condensed water, the value of effective thermal conductivity is the same as that of dry samples.

Possible effect of reverse transport of condensed water due to capillary forces and/or gravity has been studied in following experiments. The woolen and cotton samples conditioned at 95 % of relative humidity were measured inside plastic bags in two different modes:

- between the lower cold and upper hot plate
- between the lower hot and upper cold plate.

The results in Fig. 7 and 8 show the same time dependence of the effective thermal conductivity. (The only difference in the early stage of curves was a result of the position of the heat flow sensor. This was placed on the lower plate in all the experiments). Thus, no effect of capillary forces and/or gravity on the movement of condensed water was found. It is to emphasize that the needle-punched materials with rather a low content of water have been studied. The result would be probably different in the case of a high water regain and/or textile materials of parallel fiber arrangement.

The amount of heat passing through the dry and wet samples was calculated by integration of the heat flow vs. time curves. The difference $Q_x$ between these two values of heat called surplus heat (see Fig. 9) was compared with the total heat of evaporation of water present in the conditioned samples. The results are shown in Table II. The compared values are almost equal.

## Conclusions

A small amount of water present in textile materials made of hygroscopic fibers depending on relative humidity influences their thermal insulating properties in some extent. The water evaporates close to the hot side of the textile material consuming a corresponding amount of the phase change energy. The water vapor then moves toward the cold side and condenses releasing the energy. Thus, an additional mechanism of heat transport is present in wet textiles. If the content of water is small enough and the fibers are not arranged into bundles with high capillary forces, the liquid water is not transported back towards the hot side of the material. When considering textiles as thermal insulating materials, the surplus heat loss is equal to the total heat of evaporation of present water and occurs during a limited period of time, say 10 – 60 minutes, depending on temperatures of textile surfaces.

Nevertheless, to avoid this heat loss, the dry textile material can be placed inside a closed wrapping.

## References

Caps, R., Umbach K.-H., Optimierung der Waermeisolation von Polyester-Vliesstoffen, *Melliand Textilberichte* **71** (1990), pp. 440-445 [in German]**.**

Fan, J., Luo, Z. and Li Y., Heat and Moisture Transfer With Sorption and Condensation In Porous Clothing Assemblies and Numerical Simulation, *Int. J. Heat Mass Transfer* **43** (2000), pp. 2989 – 3000.

Farnworth, B., Mechanism of Heat Flow Through Clothing Insulation. *Textile Res. J.* **53** (1983), 12, pp. 717-725.

Jirsak, O., Gok, T., Ozipek, B. and Pan N., Comparing Dynamic and Static Methods for Measuring Thermal Conductive Properties of Textiles, *Textile Res. J.* **68***(1998), pp. 47-/ 56.*

Murata, K., Heat and Mass Transfer with Condensation in a Fibrous Insulation Slab Bounded On One Side By a Cold Surface, *Int. J. Heat Mass Transfer* **38** (1995), pp. 3253 – 3262.

Pierlot, A.,P., Water in Wool, *Textile Res. J.* **69** (1999), pp. 97 – 103.

Stark, C., Fricke, J., Improved Heat-Transfer Models for Fibrous Insulations, *Int. J. Heat Mass Transfer* **36** (1993), 3, pp. 617-625.

Table 1. Maximum value of thermal conductivity $\lambda_{max}$ , time at maximum value of thermal conductivity $t_{\lambda max}$ and balanced value of thermal conductivity $\lambda_{t=\infty}$ of PET, wool and cotton.

| Material | | Measured | $\lambda_{max}$ [mW/mK] | $t_{\lambda_{max}}$ [s] | $\lambda_{t=\infty}$ [mW/mK] | Water regain before the experiment [%] | Water regain after the experiment [%] |
|---|---|---|---|---|---|---|---|
| PET | 0% | in a plastic bag | 37,74 | 600 | 37,19 | 0 | 0 |
| | | without plast. bag | 38,53 | 240 | 37,08 | 0 | 0 |
| | 47% | in a plastic bag | 37,63 | 600 | 37,09 | 0,5 | 0,4 |
| | | without plast. bag | 36,97 | 3600 | 36,97 | 0,2 | 0,1 |
| | 95% | in a plastic bag | 37,61 | 240 | 36,48 | 0,8 | 0,7 |
| | | without plast. bag | 36,48 | 1800 | 36,33 | 0,6 | 0,3 |
| Wool | 0% | in a plastic bag | 36,63 | 270 | 35,51 | 0 | 0 |
| | | without plast. bag | 36,70 | 1800 | 36,15 | 0 | 2,4 |
| | 47% | in a plastic bag | 39,01 | 210 | 35,47 | 12,6 | 12,4 |
| | | without plast. bag | 44,19 | 150 | 35,29 | 12,8 | 11,2 |
| | 95% | in a plastic bag | 70,90 | 210 | 36,17 | 22,3 | 20,4 |
| | | without plast. bag | 68,74 | 210 | 36,38 | 22,4 | 16,4 |
| Cotton | 0% | in a plastic bag | 36,16 | 360 | 35,79 | 0 | 0 |
| | | without plast. bag | 37,70 | 5400 | 37,70 | 0 | 1,9 |
| | 47% | in a plastic bag | 39,87 | 180 | 35,77 | 5,6 | 5,5 |
| | | without plast. bag | 39,67 | 210 | 34,26 | 6,7 | 5,3 |
| | 95% | in a plastic bag | 68,16 | 150 | 37,27 | 13,9 | 12,1 |
| | | without plast. bag | 72,24 | 180 | 37,18 | 14,6 | 9,5 |

$x = 36{,}9902$ mW/mK
$S = 0{,}3488$ mW/mK
$CV = 0{,}94\%$

Table 2. Quantity of water in cotton and wool samples $\mathbf{M_{H2O}}$, calculated evaporating energy of indicated water quantity $\mathbf{c_s.M_{H2O}}$ and experimentally measured surplus heat $\mathbf{Q_x}$.

| **Material** | **$M_{H2O}$ [g]** | **$c_s.M_{H2O}$[J]** | **$Q_x$ [J]** |
|---|---|---|---|
| Cotton | 1,463 | 3541 | 3830 |
| Wool | 2,174 | 5262 | 5375 |

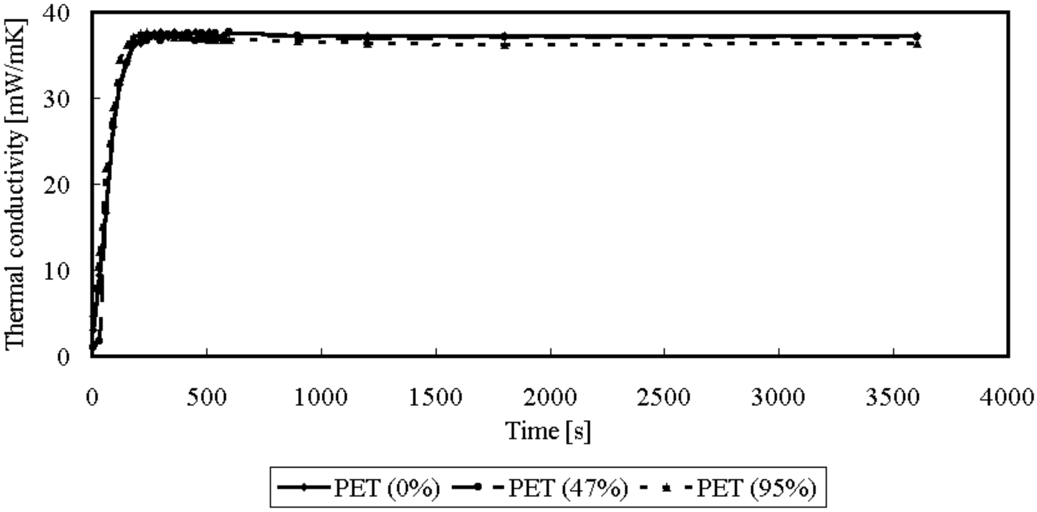

Figure 1. Thermal conductivity of PET. Measured in a plastic bag.

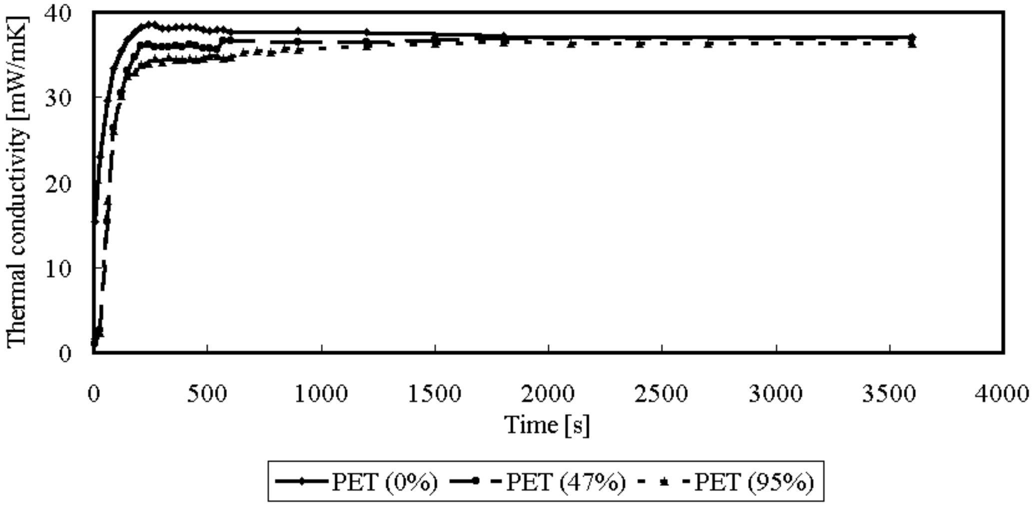

Figure 2. Thermal conductivity of PET. Measured without plastic bag.

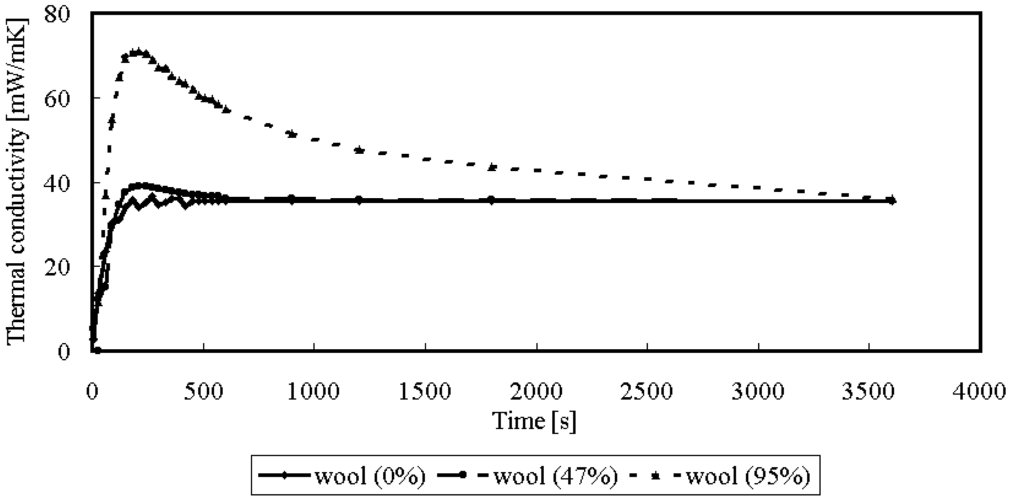

Figure 3. Thermal conductivity of wool. Measured in a plastic bag.

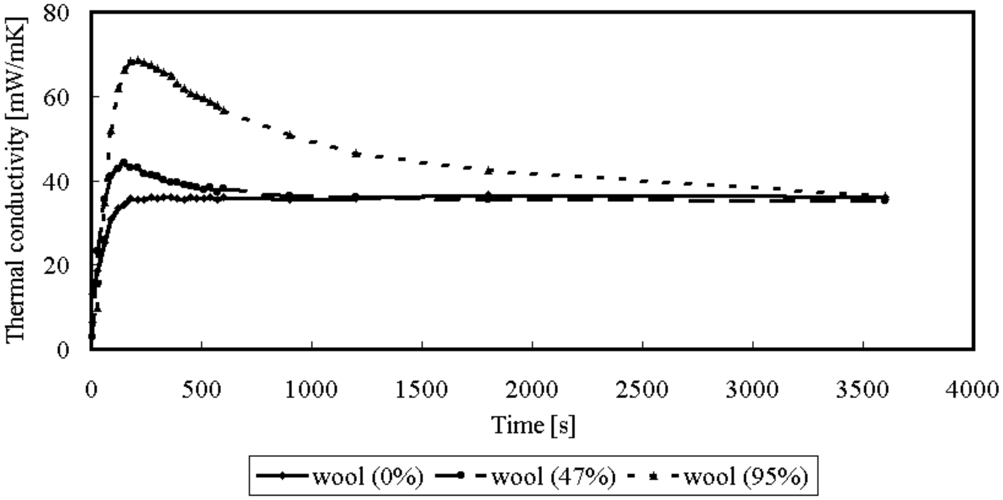

Figure 4. Thermal conductivity of wool. Measured without plastic bag.

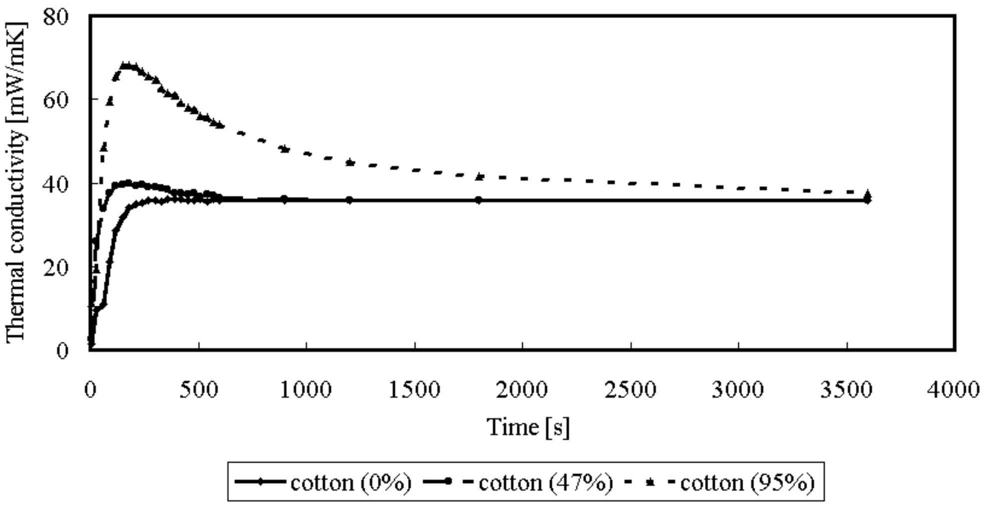

Figure 5. Thermal conductivity of cotton. Measured in a plastic bag.

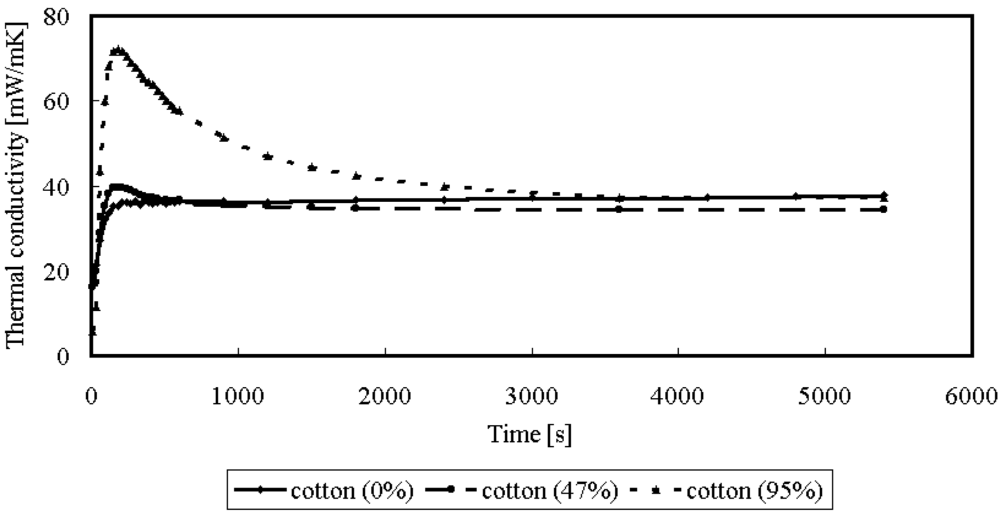

Figure 6. Thermal conductivity of cotton. Measured without plastic bag.

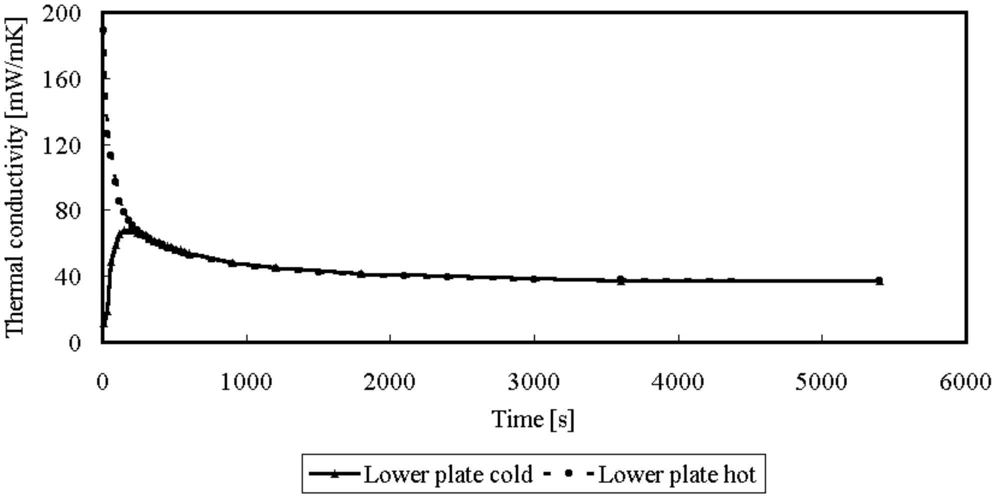

Figure 7. Thermal conductivity of cotton (95% R.H., measured in a plastic bag).

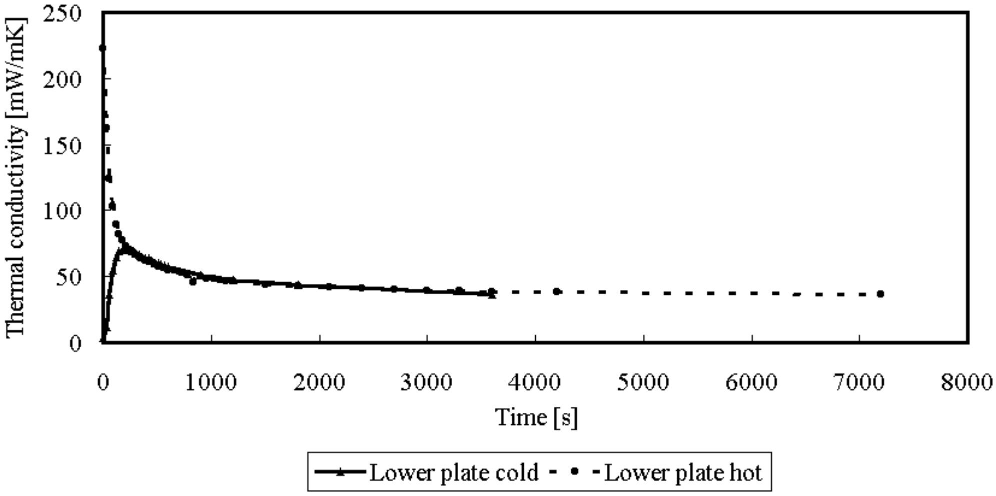

Figure 8. Thermal conductivity of wool (95% R.H., measured in a plastic bag).

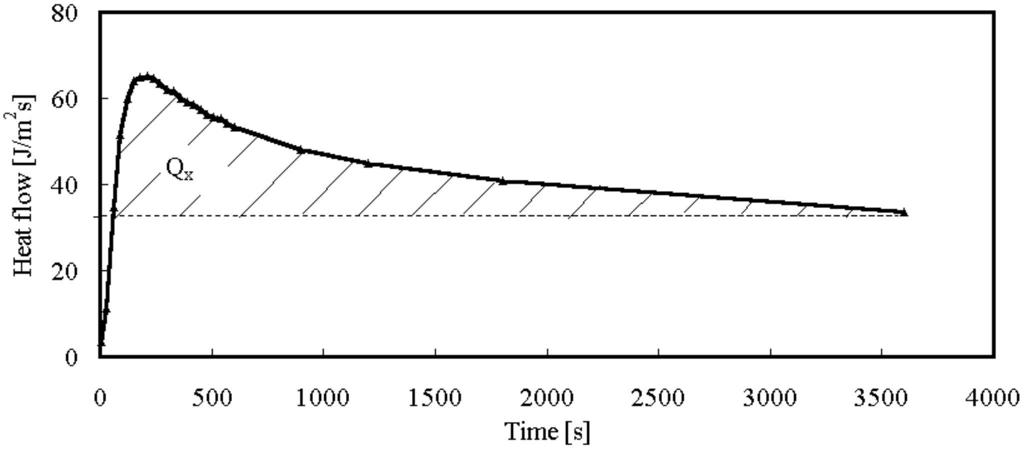

Figure 9. Schematic diagram for calculation of surplus heat Qx.