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Comparison of the Burning Process of Multilayer Fabric Packet's with the Heat Conduction Process

Abstract
In this study, a comparison of the burning process of a multilayer fabric packet with heat conduction through this packet was carried out. The values determined from the burning were compared with those obtained from the temperature measurements during heating the packet. Fabric, woven from metaaramid Nomex Delta TA 18.5 tex × 2 yarns were used in this investigation. Due to the similarity of the standard horizontal flammability test method to the real flammability behaviour of fabrics, Burning Cabinet Type BKD was used for determination of the flammability properties of a multilayer fabric packet. Heat flow properties were identified using an ALMEMO 2590-9 dimensional data compiler. It was found that a linear correlation exists between the burining behaviour of the multilayer fabric packet and parameters of the heat flow through the packet. The possibility of using the heat conduction process to estimate the real burning behaviour of a multilayer fabric packet without its destruction was obtained.

Key words: *flammability properties, metaaramid, heat flow, thermal conduction, multilayer packet.*

Introduction

Fabric flammability is affected by various factors, such as the raw material of yarn, fabric structure, oxygen concentration in the environment (moisture content, heat, air flow, etc.), and the effects of finishing the materials [1].

There are many structures of fabrics which are used to manufacture fire resistant clothes [2 - 4]. Such fabrics differ not only in the kind of raw material and the linear density of yarns used, but also in their structural parameters (set of warp and weft, type of weave). Companies manufacturing fire resistant clothes usually offer fabrics of their own design. Therefore, it is particularly important to determine the extent to which fibre and fabric structure affects the final burning behaviour of the product. This will allow to produce final products with suitable physical and burning properties for end use [5].

Basically, there are three principal types of fabric properties that characterise their flammability features:
1) physical properties;
2) chemical properties; and
3) thermal properties.

Physical properties include weight, structure and configuration of fabric. Chemical properties are determined by the fibers used, while the thermal properties of fabric can be defined as the textile's ability to absorb heat.

To overcome thermal hazards, heat and flame resistant fibers are used to produce thermal protective clothes. Thermal protective clothes should not ignite, should remain intact, should not shrink, melt, or form brittle chars that may break open and expose the wearer; and it should provide as much insulation against heat as is consistent with, not diminishing, the wearer's ability to perform a task [6].

Heat conduction through textiles affects their comfort characteristics. Most of the work done in this field is mainly related to understanding different modes of heat conduction; the study of different fabric parameters which are important for effective fabric insulation; the use of new materials which facilitate the use of garments for extreme as well as moderate climatic conditions; and development of new methods and mathematical models to determine the thermal properties of textiles [7].

Heat conduction characteristics are very important for thermal feeling and protection against weather conditions. Heat flow through most fabrics, especially for woven and knitted fabrics under conditions of low activity, is governed by conductive, convective and radiation transfer mechanisms due to temperature differences [9].

It is obvious that adding a layer, even with a low area mass and low thickness, to the existing layers of the fabric is very useful for thermal performance. Therefore, protective clothes must be produced from multi-layer fabrics and not from single fabrics of high area mass; because air trapped in and between the fabric layers is a good insulator. From the thermal point of view, a garment packet is a controlled thermal insulation layer. It must satisfy the requirements of a human wearer as much as possible, taking into consideration the human's limited thermal regulation abilities [10].

However, a garment packet also contains air interlayers between the fabrics. Air interlayers appear because of the variability of joining the particular layers and the surface unevenness of the garment layers, which are also caused by the properties of the fabrics from which the garment is made, their thickness, density, structure, surface particularities, material structure, thread density etc. [10 ÷ 13]. Textile fabrics also have inter-thread channels which, due to their complex geometry [10] also influence their thermal insulation properties.

There is a number of different tests used for evaluating the thermal characteristics of protective clothing, such as ease-of-

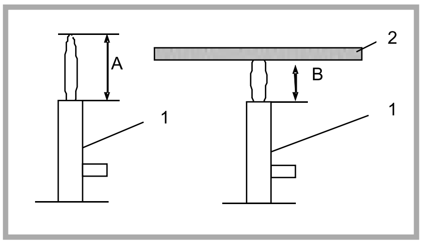

Figure 1. *Principled schema of flammability testing: 1 – gas burner, 2 – fabric packet, A – flame high equal to 4 cm, B – flame high till fabric, equal to 2 cm.*

ignition tests, flammability tests, heat-release-measurement tests, extinguish ability tests, tests for measuring the thermal insulative properties of fabrics and thermo-person full-scale garment burns [6 - 8].

Standard burning properties may be investigated only after burning the whole garment, which, as a result, is destroyed leaving no possibility of reuse. The goal of our research was therefore to explore the possibility of replacing the burning process with a heat flow process which is more applicable in research laboratories and causes no damage to textile packet or clothing.

Materials and methods

Experimental investigations were carried out with twill 2/1 fabric woven on an airjet loom PN-170 from "Nomex Delta TA" 18.5 tex × 2 spun yarns (both in warp and in weft). The set of warp of fabric investigated was 27 cm^{-1}, and the set of weft was 23 cm^{-1}. Detailed parameters of the fabric investigated and its packet are given in Table 1.

The flammability properties of the fabric were investigated using the horizontal test method according to DIN 50050-1: 1989, which is applicable to all textile materials. In accordance with the procedure, a fabric specimen was clamped wrinkle free between two plates in a horizontal position. Meanwhile the flame is positioned to ignite the surface of the fabric as opposed to the edge. The test is used to measure the ignition with reference to the burning capacity of the sample fabric. Analysis is made by measuring the time up to the start of fabric crack. The principle fabric burning scheme is shown in Figure 1.

For the temperature measurement of the fabric packet, the scheme presented in Figure 2 was applied.

Temperature measurements were carried out using heat resistant thermocouples made of Cu-CuNi wires of 0.07 mm diameter. For the temperature measurements the thermocouples were fixed to the fabric using adhesive tape. The temperature was recorded using the ALMEMO 2590-9 device which has data processing and compiler systems. During periods of investigation, the temperature measurement data gathered by the

Table 1. *Parameters of fabric investigated and its packet.*

No. of fabric layers	Thickness of fabric packet, mm	Surface density of fabric packet, g/m^2	Volumetric density of fabric packet, 10^3 g/m^3
1	0.383	199	0.520
2	0.767	398	0.519
3	1.140	597	0.524
4	1.503	796	0.530
5	1.881	995	0.530
6	2.260	1194	0.528
7	2.668	1393	0.522

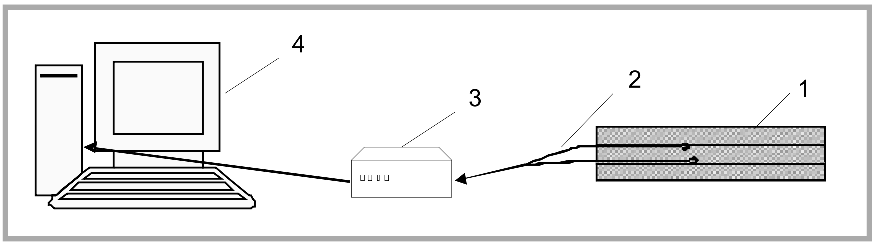

Figure 2. *Principled schema of temperature measurement: 1 - fabric packet; 2 – thermocouples; 3 – dimensional data compiler ALMEMO 2590-9; 4 – computer.*

ALMEMO data compiler was transferred to a computer using a series interface with AMR programs.

Experimental results and discussion

The aim of the experiment was to investigate the crack time of the fabric layers and the time of heat conduction through the layers. The crack time of a fabric is defined as the time when the last layer in the fabric packet is damaged. Figure 3 shows the dependence of the crack time on the number of fabric layers in a packet. The coefficients of variation of all experimental points do not exceed 10%. The coefficient of determination of the exponential curve is equal to 0.99, i.e. is sufficiently high.

The process of heat conduction through the fabric packet layers is presented in Figure 4. During this stage of the experiment, thermocouples were heated to 135 °C while measuring the temperature between the fabric layers. The temperature was measured between separate layers at several points appropriately selected. The time of heat flow when the temperature reaches 40, 60, 80, and 100 °C (not all the fabric layers, however, reached 100 °C).

The dependence of the heat flow time through the fabric layers on the number of fabric layers is presented in Figure 5. As can be seen from Figure 5, there is also an exponential correlation between the heat conduction time through the fabric layers and the number of fabric layers (the coefficients of determination are high – 0.82 ÷ 0.92).

As both dependences could be precisely described employing the exponential equation, thus, in the next stage the existence of a correlation between these parameters – packet crack time and timeof heat flow through the packet – was verified.

Correlation between the fabric crack time and its heat conduction time is presented in Figure 6. The coefficients of determination of the linear curves are high (R^2 = 0.94 ÷ 0.98), which means that the linear correlation between these two parameters is corroborated by a high level of statistical reliability.

The high correlation between the characteristics presented allows to maintain that when the thermal change in garment

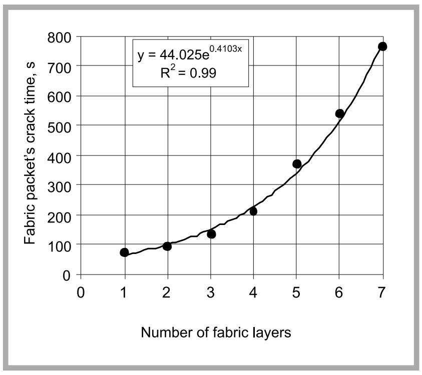

Figure 3. *Dependence of the crack time of fabric packet on the number of fabric layers.*

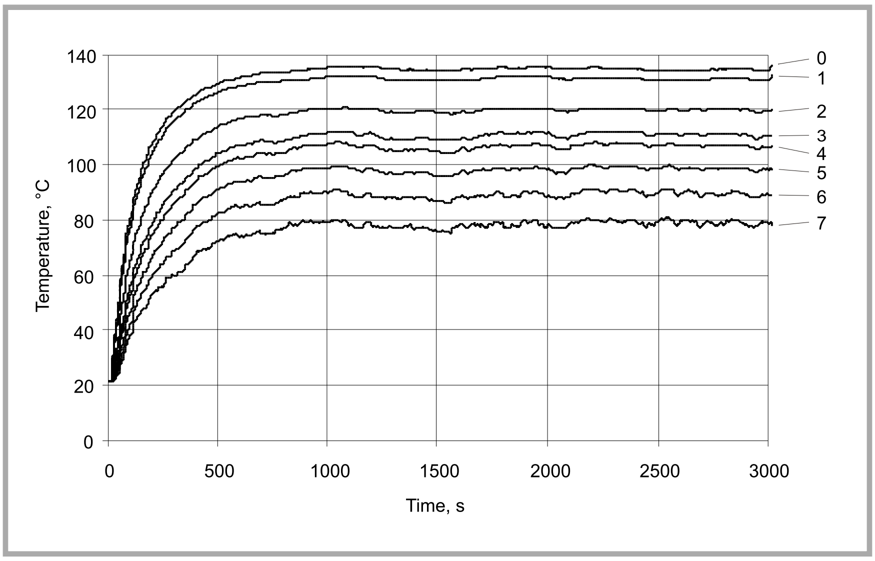

Figure 4. *Heating process for Fabric packets of 7 layers; 1 ÷ 7 variation of temperature, respectively, between 1-2, 2-3, 3-4, 4-5, 5-6, 6-7 layers.*

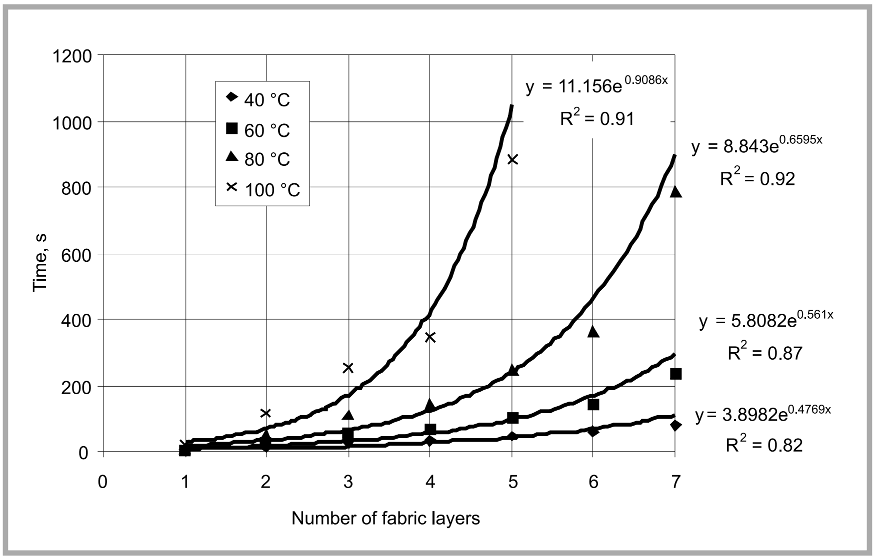

Figure 5. *Influence of heating time on temperature dynamic in 7 layer fabric packet.*

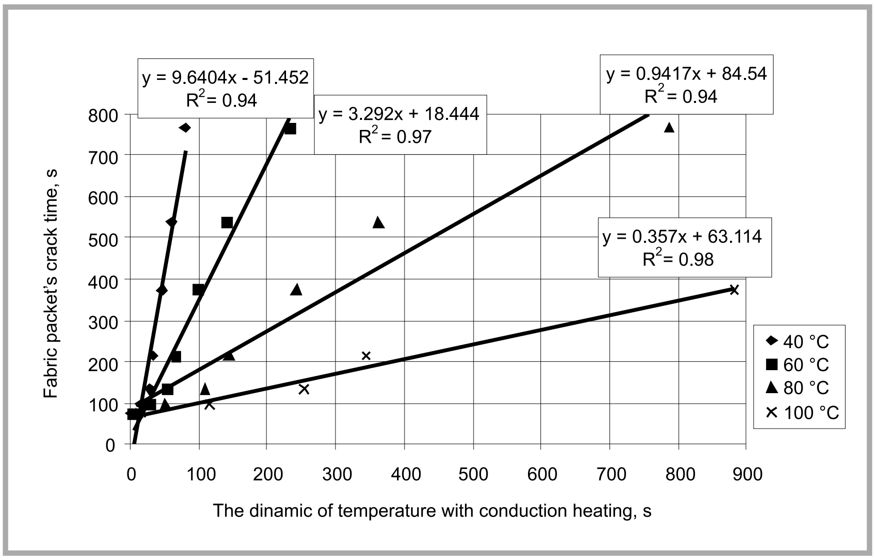

Figure 6. *Correlation between fabric crack time and its heat transfer time.*

packet after wear is known, it is possible to predict the change on crack time of such construction.

It is therefore necessary to carry out the burning and heat experimental testing of textile packet samples to represent an equation of correlation between the characteristics presented. The correlation will be further applied to predict the crack time change in clothing after wearing, without carrying out burning tests, which will be replaced by heat flow experimental testing.

If thermal permeability is found to decreases by 10%, the change in packet crack time could be calculated by inserting this value into the equation in Figure 6. It is then possible to forecast packet suitability for further wear by evaluating the level of mechanical disturbance the packet has suffered (i.e. abrasion, punching, etc.). If the fabric packet is found to be suitable for wear under thermal requirements, it can be considered suitable under burning requirements too.

To substantiate the empirical correlation between these processes (the fabric burning process and heat flow through the fabric packet layers), theoretical knowledge was employed. After carrying out an air permeability test on fabric packet layers (see Figure 7), it is possible to divide the burning process into two parts (see Figure 8). The first part (Figure 8, I), in which the heat is transferred (and the temperature is raised), is influenced by two factors:

- fabric thermal conduction (permeability), which can by defined using Fourier law:

$$dq = -\lambda \frac{dT}{dx} \quad (1)$$

here:
λ is the coefficient of thermal conduction, W/m·K;
T is the temperature, K;
x is the fabric thickness, mm.

- heat flow erupting through the fabric construction into deeper layers and thus bringing in the flow warmth, which could be theoretically defined by Newton's law:

$$dq = \alpha F dt \quad (2)$$

here:
α is the coefficient of heat transfer, $W/m^2 \cdot K$,
F is the surface area of yarns;
dt – temperature variation.

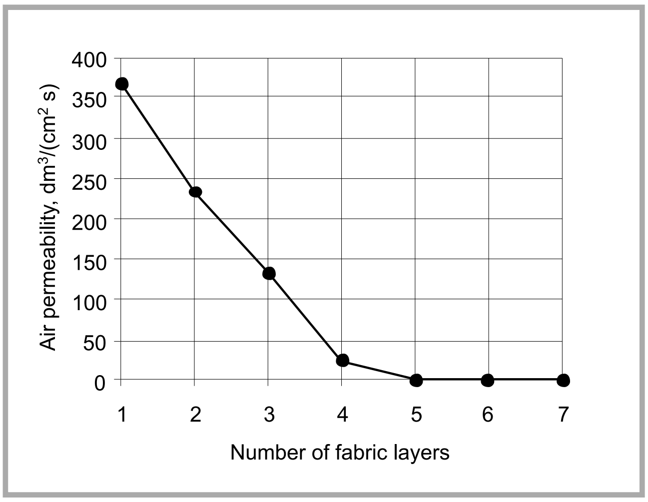

Figure 7. Dependence of air permeability on the number of fabric layers.

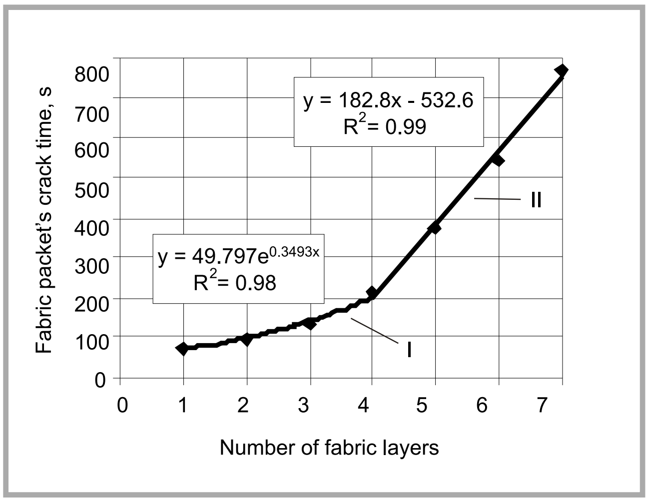

Figure 8. Dependence of the crack time of fabric packet on the number of fabric layers after dividing the burning process into two parts.

Therefore, the heat flow which gets into the outer layers can be estimated in such a way:

$$dq = -\lambda \frac{dT}{dx} + \alpha F dt \qquad (3)$$

While estimating the air permeability of fabric packet layers, as is shown (Figure 7), air penetrates until contact between the third and fourth layers (the fourth layer's measurements are near the point of inaccuracy). Further the air factor could be eliminated. Thus, for fabric packet layers from 4 to 7, the second member ($\alpha \cdot F \cdot dt$) could be put aside from equation (3). Hence, the second part of the burning process (see Figure 8, II) could be described as a process when only heat conduction take place, and therefore the distribution of temperatures has a linear character.

Therefore, fabric burning changes can thus be analysed by comparison to heat conduction changes only, after isolating the air permeability through the fabric layers.

Of course, for more precise investigations, fabric construction should be burned, but for initial tests it is possible to apply the heat flow principle. The above-mentioned dependences were obtained for the fabric woven investigated, which had been manufactured from "Nomex Delta TA" 18.5 tex × 2 spun yarns and the given fabric packet. For analogical estimation of such dependences, further investigations need to be conducted on a broader spectrum of fibres and structures. As a result, changes in fabric construction can be analysed without destroying the textile construction tested (clothing) at all.

Conclusions

- Dependencies of the burning of textile packet and the heat conduction time on a number of textile layers can be expressed in exponential equations.
- Linear dependence between the fabric packet crack time and the fabric packet heat flow time exists; therefore a change in flammability properties after wearing can be predicted by heat flow testing.
- The burning process could be analysed as a compound of two parts: the first one depends on the thickness of multilayer fabric packet and air permeability through the packet, and the second one shows the correlation with the heat flow process.
- The investigations show a possibility of analysing changes in the burning characteristics of clothing without actual burning experiments, i. e. without destroying clothes.

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