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Prediction of the Flammability of Multilayer Fabric Packet

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Level of flammability protection varies, depending on the construction and fit of the protective clothes, on the materials of fibers from which these clothes are made, oxygen and humidity concentration in the environment, even on the weave type of fabric. In this research study the prediction of flammability of the multilayer fabric packet was carried out. Fabric woven from the metaaramid Nomex Delta TA 18.5 tex × 2 spun yarns was used for the investigations. The flammability properties of tested fabric multilayer packet are determined using Burning Cabinet Type BKD for standard horizontal flammability test methods due to theirs similarity to fabric real flammability behaviour. The dependence of fabric flammability (crack time) on number of fabric layers was found. It was established that flammability process could be analyzed by two linear empirical equations. These experimental investigations were proved by a heat conduction theory.

Keywords: flammability properties, metaaramid, heat conduction, multilayer packet.

1. INTRODUCTION

To overcome thermal hazards, heat and flame resistant fibers are used to produce thermal protective clothing. Thermal protective clothing 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 [1].

Basically, there are three principal types of fabric properties that characterise their flammability features: 1) physical properties; 2) chemical properties; 3) thermal properties. Physical properties include weight, construction and configuration of fabric. Chemical properties are determined by the fibers used, while thermal properties of fabric can be defined as the textile's ability to absorb heat.

Some works considered actual effect of fabric properties, especially for one kind (for example, woven, knitted, nonwoven, etc.) of flame resistance. It is known that fabric weight, air permeability, and cover factor cause changes in the flame retardancy characteristics of fabrics [2].

It is particularly important to determine the extent, to which fibre and fabric construction affects final burning behaviour of the product. This will allow producing final products with suitable physical and burning properties for end use [3].

It is obvious that adding a layer, even with a low area mass and low thickness to the outer layer fabric is very useful for thermal performance. In some cases the garment layers can interact on the flame propagation, so that the degree of severeness of the burns increases. Inner layers can produce an insulating effect. This effect can minimize the burn by stopping the direct contact between the flame and the skin. In that way protective clothing must be produced from multi-layer fabrics and not with single fabrics of high area mass; because air trapped in the fabric layers is a good insulator. From the thermal point of view, the garment packet is a regulated thermal insulation layer. It must satisfy as well as possible the requirements of a human wearer, who has limited thermal regulation abilities [4, 5].

The most direct way to improve the safety of firefighters is creation of protective clothing with two functions: be flame-resistance and form a heat barrier. This property is very important for organic textiles, which is used near a flame sources – clothes for firefighters, racers, pilots and etc. Flame resistant, protective garments made of aramide fibres can play a key role in providing people the possibility to escape and survive a flash fire [6].

There are many structures of fabrics, which are used to manufacture fire resistant clothes [7 – 10]. These fabrics differ not only by raw material and linen or density of yarns, but by the structure parameters of fabric (set of yarns and weave) also. Each company manufacturing fire resistant clothes proposed fabrics of own design. Many researches are going in the way to find possibility to assess the used protective clothing. There are different tests used for evaluating thermal characteristics of protective clothing, such as ease-of-ignition tests, flammability tests, heat-release-measurement tests, extinguish ability tests, tests for measuring thermal insulative properties of fabrics and thermo-person full scale garment burns [1, 11, 12]. Three different non-destructive test methods – Raman luminescence, digital image analysis and colorimetry are developed [13].

The fabric permeability to air is one of very important properties of technical fabrics. Permeability to air depends on shape and value of the pores and the interthread channels, which are dependent on the structural parameters of the fabric [14, 15]. The main structural parameters, which have influence on fabric air permeability, are set, linear densities of yarns and weave. Thermal properties of fabric depend on the permeability to air too [4, 5].

The goal of present investigations is to show the possibility to predict the flammability of multilayer fabric packet using heat conduction theory.

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2. MATERIALS AND METHODS OF INVESTIGATION

Experimental investigations were carried out with twill 2/1 fabric, which was woven on an airjet loom PN-170 from “Nomex Delta TA” 18.5 tex × 2 spun yarns (both in warp and in weft). Set of warp of investigated fabric is 27 cm^{-1}, set of weft is 23 cm^{-1}.

Fabric flammability properties were investigated with horizontal test method according to DIN 50050-1:1989 [16]. The horizontal flammability test method is designed applicable for all textile materials. Fabric specimen in it is clamped wrinkle free between two plates in a horizontal position. Meantime 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 burning capacity of the sampled fabric. Analysis is made by measuring the time up to the start of fabric crack and ignition.

3. RESULTS AND DISCUSSION

This article can be presented as a continuation of the previous experiments [17].

Earlier during the experiment fabric layers’ crack time was investigated. The results were obtained with the 7 layers fabric packet. Fabric’s crack time is the time when the fabric’s structure is broken. The crack can be easily noticed because it reveals with noise [17].

In Fig. 1 it is shown the dependence of crack time on number of the fabric layers in 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. it is sufficiently high.

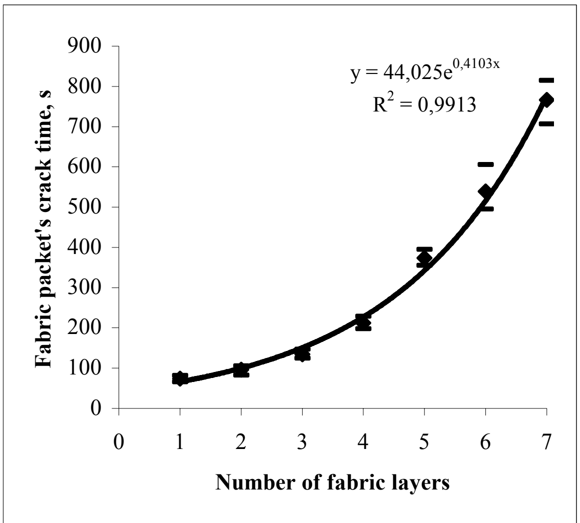

Fig. 1. Dependence of the fabric packet’s crack time on number of fabric layers

Though data presented in Fig. 1 are well described by the exponential empirical equation, there is contended with appearance when one part of the materials are permeable to air, the other one is not.

In our earlier experiments we estimated correlation between the packet crack time and time of heat flow through the packet [17]. Therefore the main thermal principles could be applied describing flammability properties.

While estimating the air permeability of fabric packet layers, it is shown (Fig. 2) that air penetrates till fourth layer.

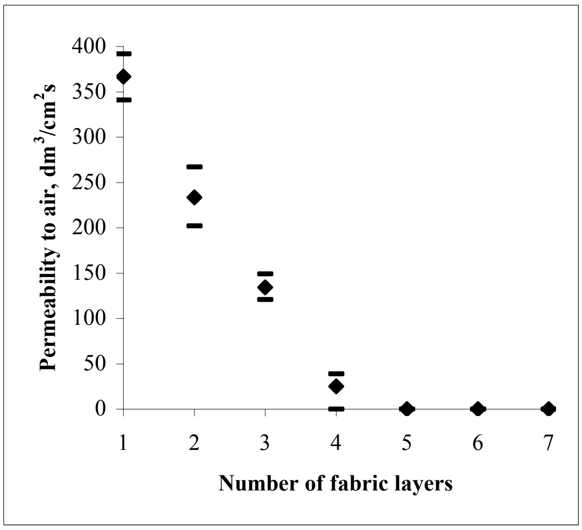

Fig. 2. Dependence of the air permeability on number of fabric layers

The fourth layer’s measurements are near to inaccuracy point. Therefore it is not possible to state unambiguously that the fabric packet consisting of four layers is permeable to air or not. From permeability to air tests it is possible to divide the burning process into two parts. In the first part the heat is influenced (and the temperature is raised) by two factors:

- fabric conduction (permeability), which is described by Fourier law:

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

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

- hot flow erupts through the fabric construction into deeper layers bringing in the flow heat, which could be theoretically described by Newton’s law:

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

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

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

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

Further, the air factor could be eliminated. Thus for fabric packet’s layers from 4 till 7 there could be put aside member from 3rd equation – $\alpha \cdot F \cdot dt$. So the second part of burning process (see Fig. 3, II), could be described as absolute heat conduction method. Therefore distribution of temperatures has linear character.

It was estimated that between the fabric multilayer packets burning behaviour and its heat flow process exists a linear correlation. Therefore it is possible to divide burning process into two parts: the first part corresponds to the permeable to air packet and the second one is not permeable. The experimental results and their empirical approximations are presented in Fig. 3.

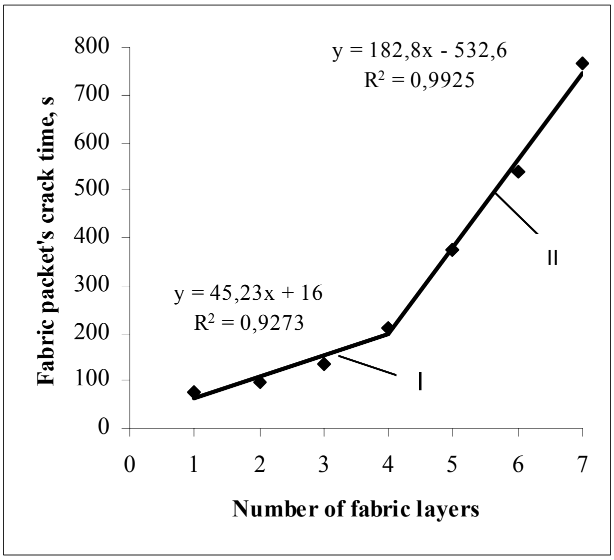

Fig. 3. Dependence of the fabric packet's crack time on number of fabric layers after dividing the burning process into two parts according the heat conduction theory

The linear dependence $y = 45.23x + 16$ is valid in the 1st part – packet is permeable to air (see Fig. 3, I). In the 2nd part (packet is not permeable to air) (see Fig. 3, II) linear dependence $y = 182.8x + 532.6$ is valid.

According to the theoretical analysis flammability dependence is not exponential (as it was remained in the beginning of the experiment (see Fig. 1)) but could be described by two linear equations. To confirm this approach the tests were carried out with the additional experimental points – multilayer fabric packet consisted from 10 layers.

The analysis of crack time on number of fabric layers is shown in Fig. 4. It was obtained that arithmetic mean value of 10th layer's crack time is 1375 seconds (coefficient of variation is 6.5 %).

When the process is divided into two linear empirical equations (Fig. 4) the crack time of the 10th layer could be calculated by the linear equation:

$$y = 182.8x - 532.6\ . \tag{4}$$

In this way the calculated crack time is $y = 1295.4s$ and the relative error δ is only 6.1 %.

The empirical equation reliability was checked using Student criterion, also. In this case, the value of Student criterion $t_\alpha = 2.1$, that is considerable lower than the statistical one – 2.78 ($\alpha = 0.95$). It means that the empirical equation satisfies the experimental results.

In the case when the crack time is evaluated using exponential equation (see Fig. 1 and Fig. 4) the calculated crack time is:

$$y = 44.025 \cdot e^{0.4103x}\ ; \tag{5}$$

$$y = 2664.5s\ .$$

The relative error δ in this case is 48.4 % and Student criterion $t_\alpha = 33.9$.

Even in the case if the additional point (10th layer of fabric packet) was used for equation calculation, the results are the same in aim (Fig. 5).

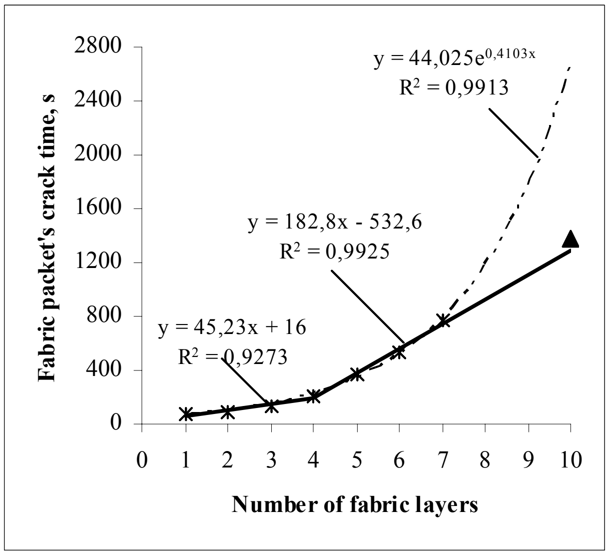

Fig. 4. Dependence of the fabric packet's crack time on number of fabric layers after dividing the burning process into two parts according to the heat conduction theory;
▲ – additional experimental point of 10th layer of fabric packet;
——— – shows two linear trendlines;
–··–··– – shows exponential trendline

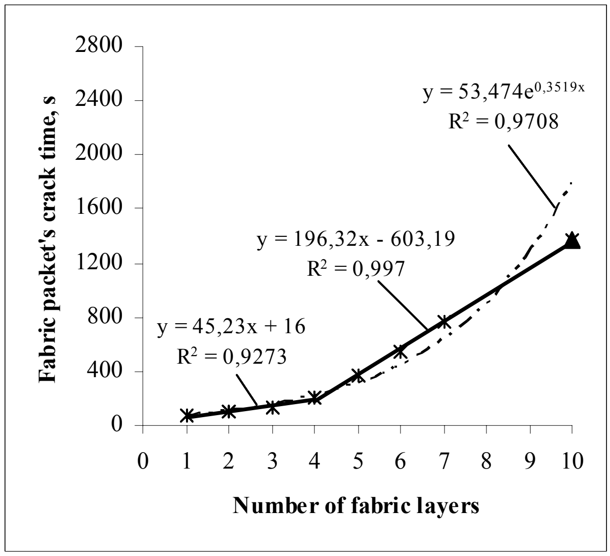

Fig. 5. Dependence of fabric packet's crack time on number of fabric layers after dividing the burning process into two parts according heat conduction theory;
▲ – additional experimental point of 10th layer of fabric packet;
——— – shows newly drawn two linear trendlines;
–··–··– – shows newly drawn exponential trendline

The relative error and Student criterion in exponential equation case are much higher then the analogous one calculated in the two linear equation case, i. e. $\delta = 23.8$ %, $t_\alpha = 11.3$ in exponential equation case and $\delta = 1.1$ %, $t_\alpha = 0.4$ in two linear equation case.

Thus the mathematical analysis proved that two linear equations evaluate the experimental results better than the exponential empirical equation.

4. CONCLUSIONS

It is shown that it is possible to divide burning process into two parts: in the first part the packet is permeable to air and the second part – it is not permeable.

Theoretical analysis showed that flammability dependence of multilayer fabric packet could be described by two linear equations.

To describe fabric packet's burning process the same principles as for the heat conduction process can be applied; the experimental investigations confirmed obtained results of theoretical analysis.

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