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Influence of Plain Knits Structure on Flammability and Air Permeability

Abstract
The investigations of the influence of knit structure, i.e. linear density of yarns, loop length and tightness factor of the knit on garment flammability and permeability to air is presented in this paper. The investigations were carried out using knits from Nomex Delta TA 18 tex×2 yarns. Four groups of knits knitted from yarns with different linear densities were used in the investigations. A good correlation between the air permeability of the knit and its burning time was found. The investigations show that an increase in the loop length of the fabrics investigated increases their permeability to air, likewise an increase in the linear density of the yarn permeability to air of knits decreases. In addition, it was estimated that the correlation between the tightness factor of the knit and its permeability to air is strong. The same correlation between the tightness factor of the knit and its burning time also exists. Consequently it is possible to predict the burning time of the new designed knit according to its tightness factor.

Key words: *knit, flammability, burning time, air permeability, tightness factor.*

Introduction

The most direct way to improve the safety of fire-fighters is the creation of protective clothing with two functions: be flame-resistant, form a heat barrier and be comfortable. The clothing set worn by fire-fighters is typically heavy, thick with multiple layers and low breathability. The reduced water-vapour permeability across the clothing layers also limits the rate of evaporative heat exchange, with the environmental conditions increasing the degree of physiological strain. Heavy construction of personal protective clothing leads to decreased functional performance as determined by a decreased walking speed, increased cardiorespiratory strain, and increased risk of injury [1-4]. It is well established that personal protective clothing may decrease mobility and may negatively affect performance [5]. Moreover the clothing set worsens the challenge of thermoregulation because of limited water vapour permeability across the clothing layers, further decreasing the rate of heat exchange [6]. The overall function is to provide the fire-fighter with adequate protection from heat, flames, and other hazardous environments. However, this protection is often achieved at the outlay on body heat balance.

Therefore it is particularly important to determine the extent to which the fibre and fabric structure affects the final burning behaviour of the product. This will allow manufacturers to produce final products with suitable physical and burning properties for end use. Protective clothing made from knitted fabrics and nonwoven materials are designed in such a way as to meet the specific requirements. There are established technical characteristics evaluating worn simulating conditions. It is known that burning depends on the fibre composition, but there is not much work in relation to the material parameters affecting the flammability. It is important that fire-fighter protective clothing prove to be sufficient protection and meet ergonomic requirements [7].

High thermal protection can be achieved by wearing multilayer or thick textile materials; but this prevents good ventilation and thus causes high heat stress to the wearer, thereby reducing their work efficiency in battles against wild fires [8]. The performance of each layer of fire-fighters' protective clothing has a significant influence on the level of protection provided. In general, the protection offered by fire-fighters' protective clothing is expected to deteriorate over time, but it is still uncertain how destructive different exposures are and how long a piece of fire-fighters' protective clothing can continue to protect to an acceptable level. The fabric structure, weight, thickness, and fibre types affect the flammability performance of single-layer fabrics, which is consistent with the thermal protective performance of fabrics. Fabric comfort performance can be reflected by a combination of its air permeability, thermal resistance, and moisture evaporation; all of these are governed also by the same structural factors of fabrics. However, in actual fire situations exposed to high heat, a thermal protective gear assembly is not composed of a singe-layer of fire resistant fabric, but often more than two layers including an outer layer and underwear.

Using inherently flame retardant textile materials or treating fibres or fabrics with special flame retardant chemicals, one can obtain flame resistant fabrics. The requirement of flame retardant clothing includes the ability to offer protection from flames without compromising the comfort property and durability of such flame retardancy [9].

Knitted fabrics are commonly used because of their excellent mechanical and comfort properties. They possess high extensibility under low load, allowing comfortable fit on any part pulled. The advantages of using knitted fabrics, as opposed to conventional fabrics, lie in their low cost, improved barrier properties, adequate strength, and comfort properties. They are also lightweight and flexible. Commonly knits are used for fire–fighters' underwear, socks, gloves, helmet liners.

Due to the manner in which yarns and fabrics are constructed, a large proportion of the total volume occupied by a fabric is usually airspace [10]. The distribution of this airspace influences a number of important fabric properties. The air permeability and the porosity of a knitted structure will influence its physical properties, such as the bulk density, moisture absorbency, mass transfer and thermal conductivity [11, 12]. Some works have considered the 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 the cover factor cause changes in the flame retardancy characteristics of fabrics [13], but these approaches are too general to represent one particular burning behaviour of a fabric [14].

Fabric permeability to air is one of the most important properties of technical fabrics. Permeability to air depends on the shape and value of pores and inter-thread channels, which are dependent on the structural parameters of the fabric. The main structural parameters which have an influence on the air permeability of knits are the structure and linear densities of yarns, the course and wale densities, and the knitting pattern. The thermal properties of fabric also depend on the permeability to air [15]. On the other hand, higher air permeability increases usage comfort [16], which is very important for users, especially for knitted head garments – helmet liners. If clothing materials and the structure of garments can allow the evaporation of perspiration and ventilation in addition to thermal protection, this will also affect the heat balance of the body [8, 17].

Designing a new fabric requires to predict its behaviour before the production of fabric. Therefore investigation on the influence of various parameters of fabric properties and creation of a fabric design in accordance with the characteristic of relationships determined is very topical. While protective clothing is being continually improved and lightened, the requirement for adequate environmental protection is generally contradictory to the desire for adequate ventilation. Therefore, the design of fire-fighter clothing is a compromise between protection and comfort.

The goal of our research was to investigate the possibility of manufacturing a garment from knitted fabrics with lower flammability and higher comfort by changing only the structure parameters of the knit, i.e. the linear density of yarns and loop length of knits.

Materials and methods

In order to define the effect of different structure knitted fabric constructional properties on flammability and permeability to air, the density of knitted fabric together with other structural factors were determined. Fabrics knitted in a single jersey pattern from Nomex Delta TA yarns, which are used for fire-fighter protective clothing manufacture, were used for the investigations. This kind of yarn was chosen due to its frequent use for fire-fighter clothing manufacturing. The knits were manufactured on a circular one-bed 14E gauge knitting machine. 11 knitted fabrics typically worn by fire-fighters under protective clothing as underwear or a helmet liner, comprising of 3 combinations for variant I, 6 combinations for variant II and 1 combination for variants III and IV, were produced. These combinations differ in loop length and linear density of yarns. Characteristics of the knitted fabrics tested are presented in ***Table 1.***

***Table 1**. Characteristics of knitted fabrics tested. **Note:** the relative error of all counts is less than 5%.*

Variants	Yarn linear density, tex	Course density P_v, cm^{-1}	Wale density P_h, cm^{-1}	Loop length l, mm	Surface density M, g/m^2	Tightness factor TF
I-1	18.5 × 2	9.5	8.25	5.10	147.89	11.93
I-2	18.5 × 2	7.0	6.50	6.32	106.40	9.64
I-3	18.5 × 2	6.0	6.00	6.90	91.91	8.83
II-1	18.5 × 2 × 2	10.5	8.50	4.80	317.02	17.92
II-2	18.5 × 2 × 2	9.5	8.50	5.01	299.37	17.17
II-3	18.5 × 2 × 2	10.0	8.25	5.10	311.36	16.87
II-4	18.5 × 2 × 2	8.5	7.50	5.72	269.84	15.03
II-5	18.5 × 2 × 2	7.5	7.00	6.32	245.53	13.61
II-6	18.5 × 2 × 2	6.5	6.50	6.90	215.73	12.46
III-1	18.5 × 2 × 3	11.0	8.00	5.10	498.17	20.66
IV-1	18.5 × 2 × 4	12.0	7.25	5.10	656.68	23.85

All experiments were carried out in a standard atmosphere for testing according to Standard ISO 139:2002. Structure parameters of the knitted samples were analysed according to British Standard BS 5441:1998.

The tightness of the knits is characterised by the tightness factor [18]:

$$TF = \sqrt{T} / l, \quad (1)$$

where T – factual linear density of the yarn in tex, l – stitch length in cm.

The flammability properties of the knitted fabrics 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. The horizontal flammability test was used, and the burning time from the start until fabric of packet break-up was measured. The height of the flame was 4 cm and the distance between the flame source and materials investigated was 2 cm.

The air permeability was investigated according to Standard EN ISO 9237:1995 using a pressure of 200 Pa. Average values of all tests were calculated from the five conducted.

The coefficients of variation for all the tests do not exceed 5%.

Results and discussions

This article can be presented as a continuation of the previous experiments [19]. During the earlier experiments, the influence of knitted fabric structure on garment flammability, i.e. the number of yarns in a loop and comparison of the results with those of a multilayer packet were investigated. Results were obtained for single yarn as well as folded yarns from two, three and four single yarns. The investigations showed that using the number of yarns in the loop, it is possible to increase the burning time of the knit more than using the same number of knits in the packet. Such a kind of knit is proposed for garments which do not need low rigidity and/or high air permeability [19]. As for the wearer's comfort, good air ventilation is necessary since protective clothing serves the purpose of eliminating or reducing the effects of environmental stress factors. Adequate protection is often obtained only at the expense of considerable restrictions on body heat balance.

In the first step, we used all 11 fabrics described in ***Table 1*** to evaluate the effects of knitted fabric structural parameters (yarn linear density, loop length, surface density) on flammability and permeability to air. After the physical tests, we conducted a horizontal flammability test for each fabric specimen.

When designing fabric flammability characteristics, attention needs to be

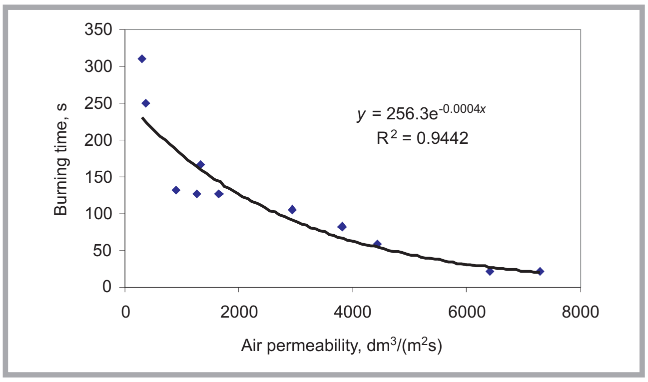

***Figure 1.** Correlation between the burning time and its permeability to air of knitted fabric.*

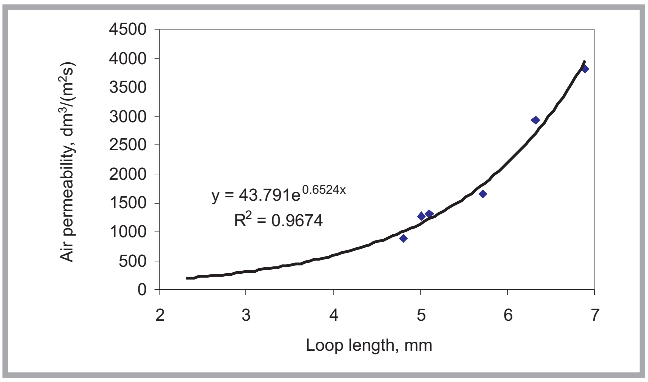

***Figure 2.** Influence of loop length on the air permeability of knits.*

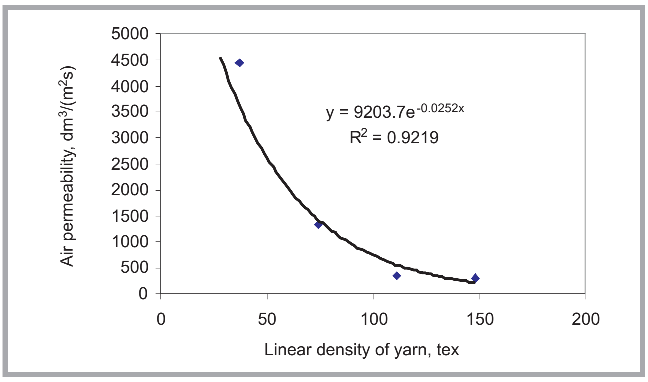

***Figure 3.** Influence of the linear density of yarns on the permeability to air of knits.*

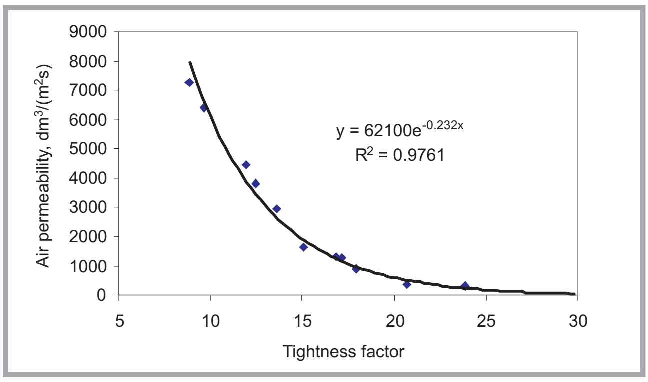

***Figure 4.** Influence of a fabric's tightness factor on the permeability to air of knits.*

paid to the fabric structure parameters directly related to the fabric voids: yarn linear density, course and wale density, their proportion, loop length, and fabric tightness factor. Fabric flammability depends on many factors, one of which is the permeability to air. One indicator of the technical properties of fabric that may be considered is the amount of fabric permeability to air. In literature it was found that permeability to air as a design parameter could be used if fabrics were woven in the same type of weave. The analysis showed that when fabric permeability to air decreases the burning time increases. Moreover fabric permeability to air decreases when the fabric density increases [20].

Such a tendency was also evaluated in our investigation. During the investigations, the influence of knit structure parameters on flammability, i.e. burning time and permeability to air was investigated. In this experiment all eleven objects were used, which differ in the linear density of yarns and loop length. The correlation between these two properties is presented in ***Figure 1***.

The coefficient of determination of the exponential curve is equal to 0.9442, i.e. it is sufficiently high, meaning that a correlation between these two characteristics exists. In our earlier experiments [20] we also estimated the correlation between flammability, fabric or packet surface density and permeability to air. Recently knitted fabrics with a different number of yarns in a loop and multilayer packets of knits were analysed.

It is known that permeability to air depends on the fabric surface density [16], i.e. it depends on the knit's loop length and on the linear density of yarns. ***Figure 2*** shows the dependence between permeability to air and loop length when the yarn linear density of the objects investigated is the same. The evaluation is made with fabrics II-1 ÷ II-6.

As is seen from ***Figure 2***, a very good exponential dependence exists between permeability to air and loop length when the yarn linear density of the knits investigated is the same, i.e. equal to 18.5 tex × 2 × 2. The determination coefficient of the exponential curve is equal to 0.9674, i.e. it is very high, meaning that knitted fabric permeability to air depends on the loop length. It is obvious that an increase in the loop length increases the permeability to air and comfort of the wearer.

In addition, the dependence between permeability to air and linear density of yarns when the loop length of the objects investigated is constant, i.e. equal to 5.1 mm, was obtained. The dependence of these parameters is shown in ***Figure 3***. For this investigation, fabrics from all four groups having the same loop length but differing in linear density were analysed.

Analysing the data given in ***Figure 3,*** it is seen that an increase in the linear density of yarns decreases the permeability to air, which is especially evident in the first stages – the difference in the permeability to air between knits made from 18.5 tex×2 and 18.5 tex×2×2 yarns, and between knits made from 18.5 tex×2×2 and 18.5 tex×2×3 is about 3.5 times. The difference in the permeability to air between knits made from 18.5 tex×2×3 and 18.5 tex×2×4 is just 1.15 times. An increase in the thickness of knits decreases comfort and the possibility of the person being more comfortable: They cannot

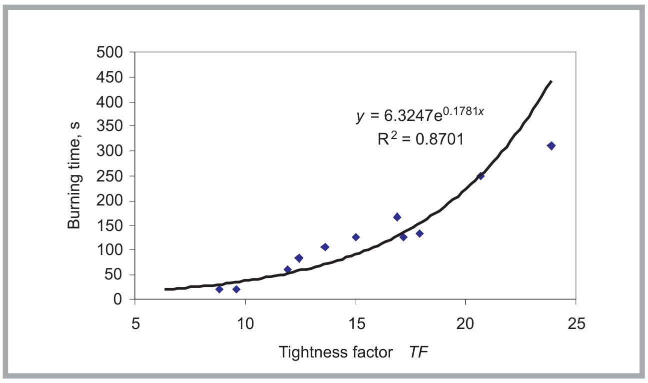

Figure 5. Correlation between a fabric's tightness factor and burning time.

function satisfactorily if they feel uncomfortable or, even worse, become incapacitated due to excessive heat stress.

The loop length of the knit and linear density of yarn are important in the parameter called the tightness factor *TF,* as suggested by Munden [18]. It is known that the tightness factor is the ratio of the area covered by the yarns in one loop to that occupied by that loop. It is also an indication of the relative looseness or tightness of the plain knitted weft structure. Therefore the dependence between permeability to air and the tightness factor was obtained (see ***Figure 4***). For this research, all fabrics manufactured, i.e. knitted with a different loop length and from yarns with different linear densities, were used.

The results presented in ***Figure 4*** demonstrate that the dependence between those parameters exists and is very strong (the determination coefficient of the exponential curve is equal to 0.9761). For fabrics with a looser structure, small changes in the tightness factor gives a marked change in the permeability to air. Meanwhile, when the structure of the knit is thick, even a great change in the tightness factor gives a low variation in the permeability to air. When the structure of the knit is fully covered by yarns (without pores between yarns), air is permitted only through the yarns. Further increasing of the knit density does not influence to the same level as in the case of loose knits, where air is generally permitted through the pores between yarns. This fact explains the physical sense of the exponential curve used in our investigation. The tightness factor can be changed through alteration of the loop length or yarn linear density or through alteration of both these parameters.

In our further research [19] it was established that the flammability (burning time) of knitted fabric correlates with the permeability to air. Therefore in the next stage the dependence between the burning time and tightness factor was investigated. As both dependences, i.e. the dependence between permeability to air and loop length and that between the permeability to air and linear density of yarns, could be precisely described employing exponential equations; thus the existence of a correlation between these parameters – the burning time and tightness factor – was verified (***Figure 5***). The analysis was also made with all fabrics manufactured.

As can be seen from ***Figure 5***, an exponential correlation between the burning time of the knits and the tightness factor exists (the coefficient of determination is sufficiently high – 0.8701). The correlation between the characteristics presented allows to maintain that when the tightness factor of the knit is known, it is possible to predict the potential burning time of such a construction. Therefore by variously combining the loop length and linear density of yarns it is possible to produce knits with various surface densities. Herewith it is possible to predict both permeability to air and flammability properties. If the proper fabric structure could be found, it would be possible to design a product with reasonable ergonomic and flammability properties.

Conclusions

- The high correlation between the permeability to air and burning time of knits was estimated.
- It is estimated that an increase in the loop length of the fabrics investigated increases their permeability to air, whereas an increase in the linear density of yarns decreases the permeability to air of the knits.
- When the loop length of knit and the linear density of yarn are considered as one parameter - the tightness factor, this can be used for fabric air permeability forecasting. The high correlation between the permeability to air and tightness factor confirms that.
- The correlation between the fabric's tightness factor and burning time allows to maintain that when the tightness factor of the knit is known, it is possible to predict the potential burning time of knits without further investigation.

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