Advance Research in Textile Engineering

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Review Article

Quasi Yarn Stabilized ROTIS Structures with Improved Thermal Insulation

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Received: August 09, 2022; **Accepted:** August 22, 2022; **Published:** August 29, 2022

Abstract

The fast and relatively inexpensive new technique of stabilization of the 3D structure based on mechanical twisting of fibre ends protruding from the fabric surface to quasi-yarns is proposed and tested. The principles and conditions of building of quasi-yarns, their cohesion dependence on technological parameters and application of this technique on the 3D nonwoven structures are shown. A suitable machinery ROTIS using new bonding technique with quasi yarns is briefly described. There are also demonstrated 3D textile structures. Second part is devoted to description of factor responsible for of high thermal insulation fibrous structures.

Introduction

Form stabilization is one of the basic nonwoven production technology steps. Textile structure made by different process, for instance, by stratification of fibers, fiber bunches, carded web, nonwovens, has to be form stabilized (shape fixed). The structure can be fixed by bonding in every fiber contact (impregnation) or in the local places of the structure (by print). Thick (3D) textile structure is therefore possible to bond in all their cross-section, or in the chosen locations as e.g. surfaces. The fibrous structures fixed on the surface have specific properties, which are interested for many of targeted applications including thermal insulation. Some of technologies allow also attachment and bonding surface reinforcing net to the surface of fibrous structures. These nets ensure properties like strength, toughness and rest of the textile structure ensures other functions, like acoustic or thermal or acoustic insulation, filtration etc. A specific task of the production technology of nonwovens is mechanical fixation of thick textile structures. In practice the mechanical bonding of such structures has been realized at special machines (Multiknit of Mayer Company) where the surface layers of the 3D textile fabric are stitch bonded only. The fiber bundles being drawn from the surface of the bonded textile fabrics are here used as the stitching material. Using this technology textile fabric bonded on both sides are necessary to be produced on two machines. The surface stitch bonding gives to the textile fabric specific properties, especially softness and shape adaptability.

The simpler method described here is to use fibers ends protruded from surface of fibrous structures for form fixing by quasi yarns. 3D textile fabrics created by special technology ROTIS are here used for enhancing of thermal insulation.

3D Nonwovens

In thick 3D textile structures the number of practically-important dimensions is three in contrast to 2D textiles (thin structures like textile fabrics) and 1D textile (yarns, ropes). Thickness of 3D nonwoven structures is made by stratification of semi-products i.e. fibres, carded webs or 2D nonwovens. Directions of this stratification can be different, predominate directions are horizontal and vertical (Figure 1).

Direction of stratification determinates an orientation of structural elements in the structure of product and significantly influences the choice of fixation principle. 3D products with horizontal orientation of structural elements, for example, cannot be fixed on the surfaces of product only. Delamination of the product in this case is evident.

The creation of a web waves (corrugates) as the basic construction element of 3D nonwoven fabric is described in work of Hanus and Jirsak [1]. For the 3D textiles manufactured through vertical folding of a web into waves the main characteristic is, that the folded structures (fibrous assemblies, nonwoven) goes through from one side to the other side (Figure 2).

The basic relations between the 3D textiles parameters and producing technology parameters are known and were already described [3]. Development of corrugated 3D textile fabrics by technology STRUTO (shape fixation by thermal bonding) and ROTIS (shape fixation by qusi-yarns) and their main applications are described in works of authors [3,10].

Today, there are two main methods of mechanical surface shape fixation of nonwoven structures that can be applied for 3D structures.

First is splicing by means of fibre bundles which is used by the MULTIKNIT machine supplied by the German company Mayer [5].

Second one developed at TUL Liberec is based on twisting of fibers ends protruding from the web surface into so-called quasi-yarns [2]. The machine for implementation of this method includes no parts performing oscillatory motion. The appearance and properties of the products of course conform to the different fixation principles. Advantage of this method is posibility to attach and fix surface reinforcing nets to the surface of fixed structures.

This method is less energy demanding than e.g. fixation by the thermal bonding and the structure or shape of the product will be not changed "(Figure 3).

Quasi-Yarn Formation

Both classic and quasi-yarns are made by fibre twisting. In

Citation: Militký J, Hanuš J and Venkataraman M. Quasi Yarn Stabilized ROTIS Structures with Improved Thermal Insulation. Adv Res Text Eng. 2022; 7(2): 1074.

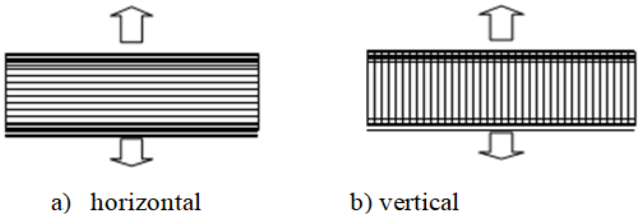

Figure 1: Basic stratification types.

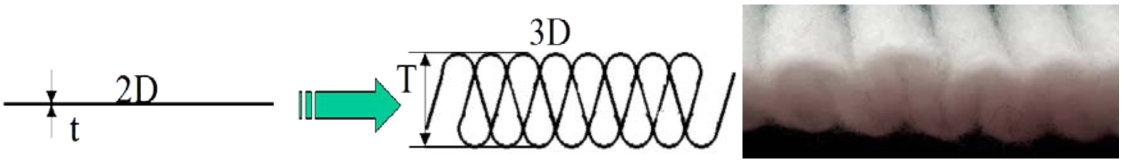

Figure 2: Principle of vertical folding (T=H is product thickness).

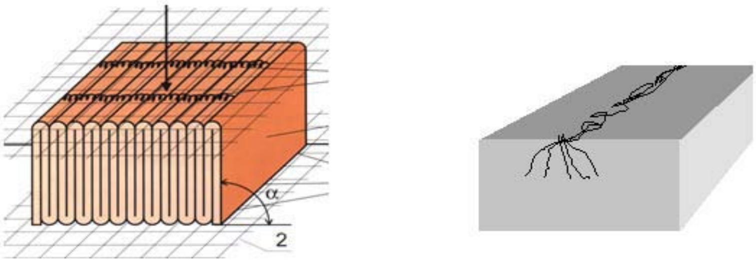

Figure 3: Characteristics of quasi-yarns fixation.

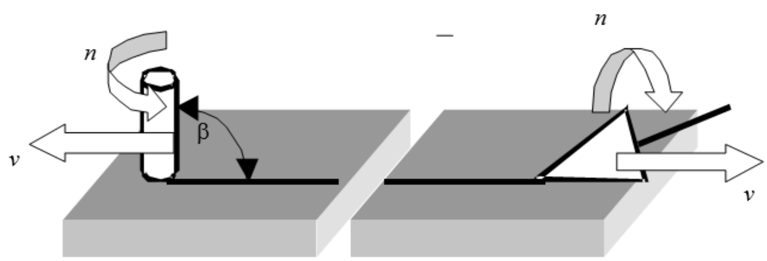

Figure 4: Principle of quasi-yarns creation.

contradiction to classic yarns, quasi-yarns are formed by twisting of protruding ends or of loose segments of fibres situated on surface of a fibrous structure.

A model of a quasi-yarn structure is illustrated in the (Figure 3). Major part represented by twisted fibres lies on the s surface, but some fibres reach the sub surface layers.

We have found that if a rotating cylinder- or cone-shaped body moves on the corrugated 3D textile fabrics surface by its base (Figure 4), it leaves behind a „track" in form of twisted fibres. The shape of this track is similar to the classical yarn and therefore is called quasi-yarn. Quasi-yarns can be laid on the corrugated 3D textile fabrics surface in optional spacing. The basic technological parameter of the quasi-yarn is apparent number of the twists per meter T [1/m] as function of number of revolutions of twisting device n per minute [1/min] and shift rate of fibrous mass movement v_1 [m/min].

$$T = n/v_1 \tag{1}$$

Precise experimental evaluation of the quasi-yarn apparent twist is very difficult.

By suitable mutual arrangement of the rotating body and the corrugated 3D textile fabrics surface, e.g. according to (Figure 5), it is also possible to bond textile fabrics together by „surface lamination". By repeated lamination it is possible to produce textile fabrics of requested thickness (e.g. 10 to 50 mm).

By analysis of the system for quasi-yarn production (Figure 4) it is possible to specify most important technological parameters, as:

- Diameter of the twisting device d;
- Revolutions of the twisting device n;
- Rate of the fibrous mass shift motion v_1;

- Inclination angle α between the twisting device and the surface;
- Contact pressure between the surface of the twisting device and the structure surface.

It is evident that the effect of the twisting device depends on its geometric shape and the roughness of its friction area.

The contact pressure value is influenced by corrugated 3D textile fabrics surface structure (orientation of structure elements against loading) and used fibre material characteristics (flexural rigidity, fibre fineness etc.).

Quasi-yarns technology may be used both for structure fixation and for lamination of specific products. Products suitable for quasi-yarn technology application can be characterized as follows:

Characteristics of nonwoven structures: The basic requirement is that fibres have to go through the nonwoven from one side to the other one. This important condition fulfils all structures based on perpendicularly corrugated thin layer (carded web, nonwoven web), or pneumatic manufactured structures. Quasi-yarn technology has been developed especially for corrugated 3D fabrics structures manufactured through vertical folding of a web e.g. according to (Figure 3).

Characteristic of reinforcing nets: Considering that during the quasi-yarn formation a rotating device has to grip loose segments of fibres going through the opening of the reinforcing net and to twist them into quasi-yarn, these openings must be sufficiently large. It is suitable to use reinforcing textiles with openings larger than 2x2 mm.

Characteristic of textiles for lamination: The surface of the both laminated textile fabrics, between which the quasi-yarn is to be formed, has to contain loose fibre segments or fibre ends that can be gripped and twisted by the rotating device into quasi-yarn.

Testing of Quasi-Yarns Cohesion

For testing of quasi-yarn strength, it is not possible to use standard methods as for classic yarn testing. This is because it is difficult to separate quasi-yarns from the product surface as well as because a quasi-yarn separation interferes with cohesion [4].

For studying of technological parameters influence on the quasi-yarn cohesion we proposed a method according to the scheme in (Figure 6).

As a parameter characterizing the quasi-yarn "cohesion" we consider the bond strength of two reinforcing nets strips.

The dependence of cohesion S [N] on the shift velocity v of the corrugated 3D textile fabrics by using cylinder body rotating with constant revolutions n = 815 per minute is shown in (Figure 7).

The dependence of cohesion S [N] on the revolutions n of rotating cylinder body when the shift velocity v = 0.33 m/min and thickness of fabric is 3 mm is shown in (Figure 8).

It is visible than cohesion force dependent on the shift rate of the corrugated 3D fabrics mainly. By proper selection of these parameters is possible to obtain cohesion force about 30 N for quasi-yarn with twist about 6006.6 1/m.

ROTIS Principle

The main characteristics of conventional nonwoven products are their constant thickness and density. Non-conventional products are characterized by locally different density mainly. One possibility how to create 3D product based on conventional 2D nonwoven web is shown in (Figure 2).

For forming of 3D textile structures with prescribed thickness in the range 4 till 60 mm based on conventional planar web with thickness 0, 2 till 2 mm the ROTIS device was invented and designed. Principle

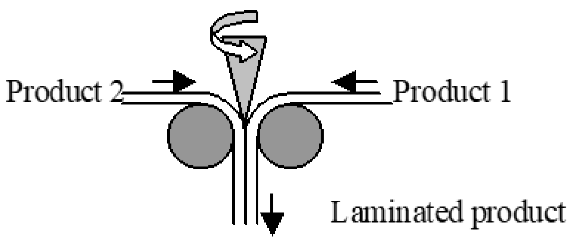

Figure 5: Surface lamination by quasi-yarns.

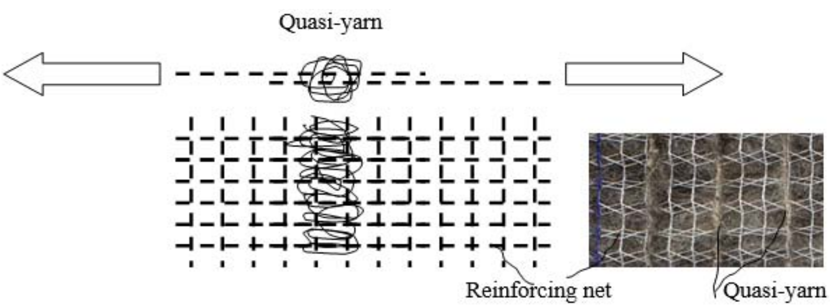

Figure 6: Testing quasi-yarns cohesion.

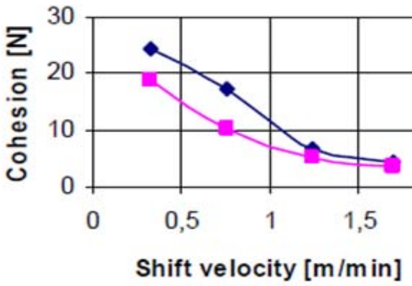

Figure 7: Quasi-yarns cohesion as function of shift rate (blue line is for fabric thickness 6 mm and red for thickness 3 mm).

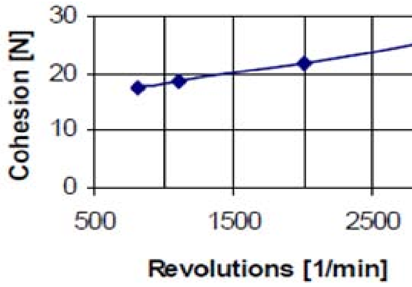

Figure 8: Quasi-yarns cohesion as function of number of revolutions.

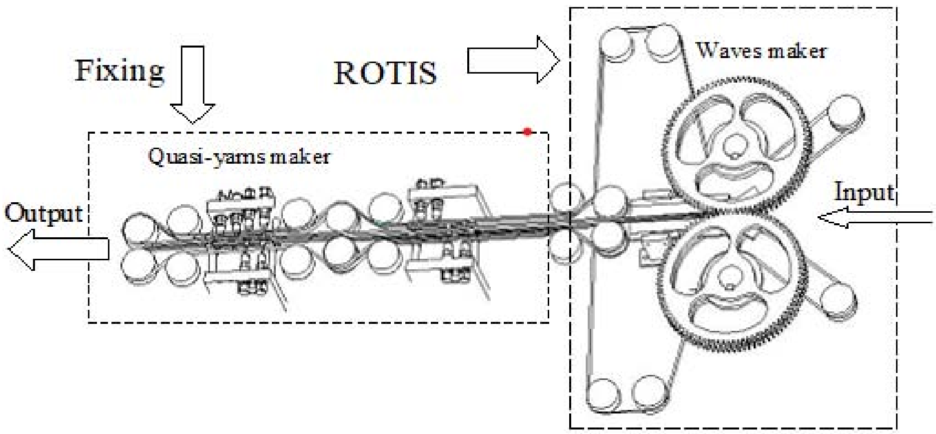

Figure 9: Combination of ROTIS and quasi yarns formation.

is preparation of perpendicularly laid structures by deformation between toothed gears. Combination of ROTIS principle with quasi yarns formation is shown in (Figure 9).

ROTIS type 3D structures can be prepared in huge variation of porosities due to changing density of "waves". Provided that a wave is the basic building unit of the product, we can easily deduce the basic relations between the parameters of technology and the geometric dimensions of the product [3]. If we substitute wave simply by triangle with height equals the height of the product, the product thickness H [m] is expressed as

$$H = \frac{A v_1}{2 v_3} \qquad (2)$$

where v_1 [m/s] is web input rate, v_3 [m/s] is rate of the working roller and A [m] is tooth pitch of the working roller.

The wave number of ROTIS structure [number of waves per 1 m] w_n is equal to

$$w_n = \sqrt{\frac{t^2 - 1}{4H^2}} \qquad (3)$$

and required thickening of starting web t is equal to

$$t = \sqrt{4H^2 W_n^2 + 1} \qquad (4)$$

Using of these relations between the product parameters H, w_n and technological parameters v_1, v_3, it is possible to produce 3 D corrugated nonwoven products of the required macro geometrical structures (Figure 10).

Using the settings v_1, and v_3 rates are constant, machine produces product with constant thickness and density which is common.

By means of mutual laminating of planar textiles it is possible

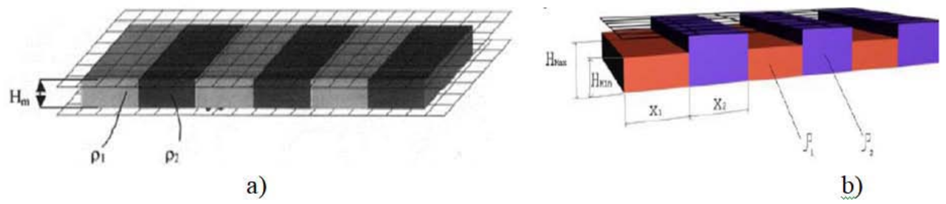

Figure 10: ROTIS products with different macro geometrical structures a) different density b) different thickness and density.

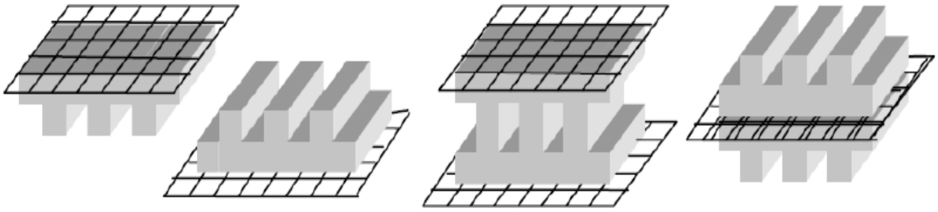

Figure 11: Product created by lamination.

to obtain other types of non-conventional products, like “hollow” products or products of structured surface, for instance according to the scheme in (Figure 11).

Thermal Insulation

There exist a lot of approaches how to calculate thermal resistance in units *clo* of clothing for assuring comfort for selected climatic conditions (temperature, wind speed, altitude) and human activities [7]. Simple is calculation of optimal thickness H_{opt} or *IREQ* [6].

For design purposes there are three main steps how to optimize textile layer composition and thickness, which are tuned by using ROTIS products.

1. Selection of suitable fiber type. Usually the fine round fibers from polyester or Polypropylene (PP) are recommended. PP has lowest thermal conductivity of any natural or synthetic fiber (6.0 compared to 7.3 for wool, 11.2 for viscose and 17.5 for cotton). PP fibers retain more heat for a longer period of time, have excellent insulation properties in apparel, and combined with its hydrophobic nature keeps wearer dry and warm. PP is warmer than wool. Main advantages of PP are: outstanding chemical resistance, abrasion resistance, durability, low density, easy form ability, stain and soil resistance, simple wash-ability and quick drying. Main disadvantages of PP are: low recovery and poor resilience, low moisture absorption, low thermal and UV stability (thermal shrinkage), high crystallinity, poor texturizing capability, creep due to low Tg (-15 to -20°C), low stiffness, flammability which melts and burns like wax and poor dyeability (dyeing in mass).

From point of view of porosity, the finer crimped fibers with complex cross section profile are the best ones. Decreasing fiber diameter tends to increase the thermal resistance of fibrous insulation materials. The effect is most pronounced at low bulk densities and high porosity, where there is a large separation between fibers, and where thermal radiation is the dominant mode of heat transfer.

Generally, the key factor is construction of planar textile layer which is responsible for total porosity of system mainly. Synthetic materials are week in the case of attack of flame when they are source of secondary injuries due to creation of melt. Promising material are fine wool fibers beside their relatively high thermal conductivity.

2. Construction of plane structure with sufficient porosity *Po* air permeability *Ap* and planar mass *W* in *gsm*. Wowed and knitted structures are generally worse in comparison with nonwovens because some pores are higher which leads to the unwanted increase of air permeability. Nonwoven structures can be tailor made by simple modification of fabrication process. Especially perpendicularly laid structures of ROTIS type can be prepared in huge variation of porosities due to changing density of “waves”. Thickness of these structures can be varied as well. The thermal conductivity of these structures λ_c can be simply predicted from two phase models.

3. Selection of **required thickness** of insulation layer. This thickness can be predicted from knowledge of external conditions (temperature, wind speed, altitude and human activities) and from thermal conductivity of textile layer λ_c. From predicted thickness H_{opt} and λ_c it is simple to calculate thermal insulation in *clo* and compare results with IREQ for checking the final comfort. There are two possibilities how to made required thickness. Standard is layering for which is not simple to consolidate structure. Layering should be therefore accompanied by proper technology ensuring no peeling. More promising is technology ROTIS which is able to prepare textile layer with prescribed thickness.

The optimal thickness H_{opt} of textile layer with thermal conductivity λ ensuring comfort in conditions:

1. human is sitting in the room at temperature T_a, without sweating, metabolic rate is 1 *Met*,
2. cloth is transferring 76% metabolic heat i.e. 44.1963 W m^{-2},
3. skin temperature is 33°C,

is expressed by equation

$$H_{opt} = \left(\frac{33 - T_a}{44{,}1963} - 0{,}268\right)\lambda \quad (5)$$

For room temperature 21°C, is optimal textile layer thickness

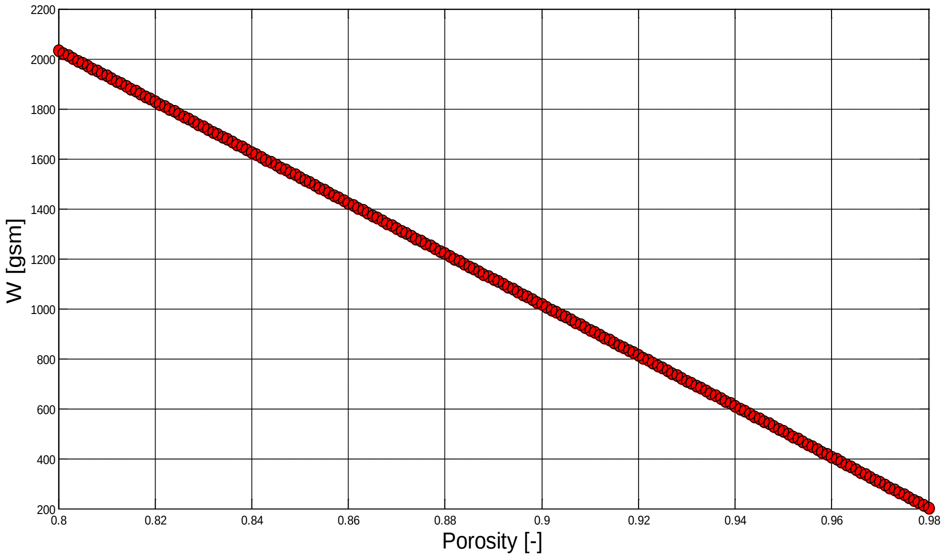

Figure 12: Dependence of planar mass [g m^{-2}] on porosity *P* for the thermal conductivity 0.030 [W m^{-1}K^{-1}] and fibre density ρ_F = 1300 [kg/m^3].

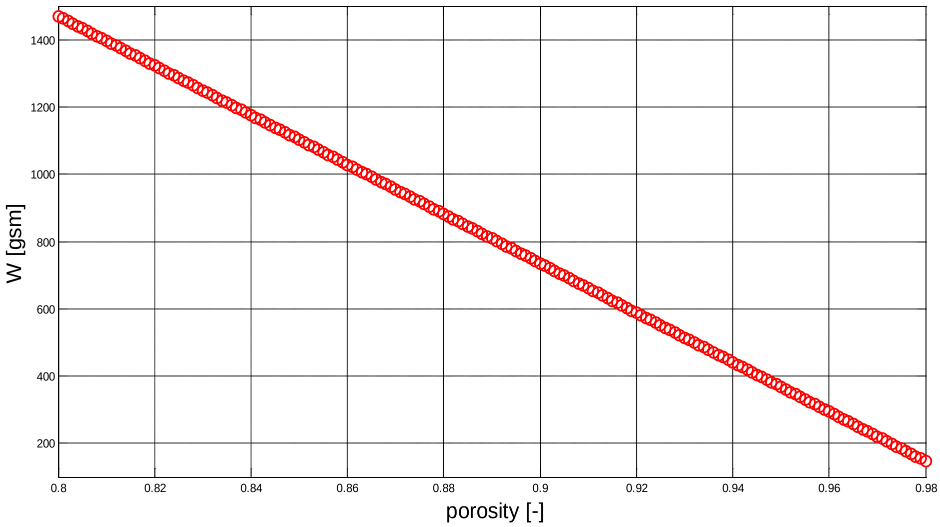

Figure 13: Dependence of planar mass [g m^{-2}] on porosity *P* for the thermal conductivity 0.030 [W m^{-1}K^{-1}] and polypropylene fibre (density ρ_F = 940 [kg/m^3]).

equal to $H_{opt} = 0.00352\ \lambda$, and for temperature -20°C is H_{opt} = 0.9312 λ.

Required clothing insulation index (*IREQ*) represents the thermal stress associated with the exposure to cold environments expressed in m^2 K/W or by *clo* [6,8]. The *IREQ* is applied to continuous, intermittent and occasional exposure either for indoor or outdoor working conditions. Two indices based on *IREQ* are used. Clothing insulation required for heat balance ($IREQ_{min}$) and clothing insulation required for comfort ($IREQ_{neutral}$). At $IREQ_{min}$ the person can keep "high strain" body temperature T_{sk} = 30°C At $IREQ_{neutral}$ the person can keep normal body temperature T_{sk} = (35.7+0.0285 M) °C

It is well known one of governing factor of thermal comfort is thickness of textile layer *H*. Thermal conductivity is mainly dependent on the total porosity and for standard structure is in relatively narrow region 0.03-0.08 W m^{-1} K^{-1}. It will be useful to interrelate construction parameters of nonwoven structures and their thermal insulation I_c expressed in thermophysiological units Clo. The total volume porosity of nonwoven fabrics P [-] is given by relation.

$$P = 1 - \frac{w}{H\rho_F} \quad (6)$$

where the planar mass - gsm W [kg m^{-2}] (usually [g m^{-2}]), thickness - H [m] (usually [cm]) and fiber density - ρ_F [kg/m^3]. The gsm W is then equal to:

$$w = (1-P)H\rho_F \quad (7)$$

It is visible that the planar mass *W* is directly proportional to the fabric thickness. The required thermal insulation is defined by eqn.

$$I_c = \frac{H}{0.155} \quad [clo] \quad (8)$$

where $\boldsymbol{\lambda}$ [W m^{-1} K^{-1}] is thermal conductivity of fabric. For given thermal conductivity $\boldsymbol{\lambda}$ [W m^{-1}K^{-1}] and I_c [clo] is required thickness

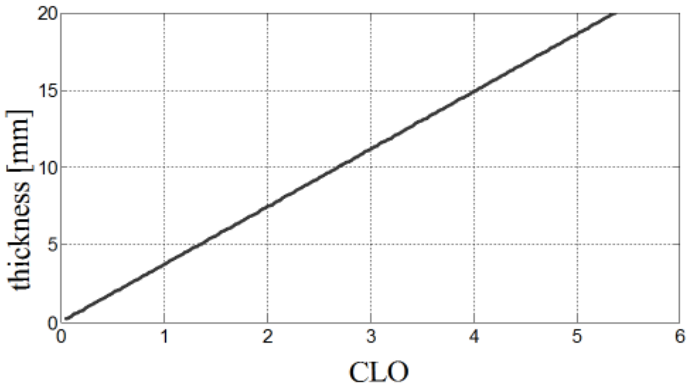

Figure 14: Minimum thickness of highest insulating textile layer (with the same thermal conductivity as air) for different *clo*.

H [m] equal to:

$$H = 0.155\ \lambda . I_c \quad (9)$$

For given porosity *P* [-] and fiber density ρ_F [kg/m^3] is the planar mass W [kg m^{-2}] equal to:

$$W = 0.155\ (1-P).\ \lambda . I_c . \rho_F \quad (10)$$

Usually the I_c can be computed from external weather conditions and human activities. Simple prediction of fabric insulation I_c *clo* as function of air temperature T_a only for no extra human activities and no windy conditions is given by regression relation [6]

$$I_c = 1.372 - 0.01866\ T_a - 0.0004849\ T_a^2 - 0.000009333\ T_a^3 \quad (11)$$

For T_a = -25°C is I_c = 1.6813. The dependence of planar mass *W* [g m^{-2}] on fabric porosity *P* for the fabric thermal conductivity 0.030 [W m^{-1}K^{-1}] and fibre density ρ_F = 1300 [kg/m^3] is shown in (Figure 12).

It is visible that for fabric porosity 0.96 is corresponding planar mass equal to 400 g m^{-2}. It is then practically impossible to construct the effective insulating layer for outside temperature – 25°C with planar mass below 200 g m^{-2}. For very high porosity 0.9800 (i.e. the only 2% of fabric is fibrous phase) is still planar mass 203.2650 g m^{-2}.

For the case of **polypropylene** i.e. fibre density ρ_F = 940 [kg/m^3] is dependence of planar mass *W* [g m^{-2}] on fabric porosity *P* for the thermal conductivity 0.030 [W m^{-1}K^{-1}] shown in (Figure 13).

It is visible that the planar mass is lower but still for very high porosity P = 0.9700 is required planar mass *W* = 220.46 gsm.

The fabric density ρ_T is defined as function of the planar mass - gsm and thickness H

$$\rho_T = \frac{W}{H} = \rho_F v_F + \rho_a(1-v_F) = \rho_a + v_F(\rho_F - \rho_a) \quad (12)$$

where v_F is volume portion of fibrous phase ρ_F is fiber density and ρ_a is air density. The air density at 21°C, 65 % relative humidity and elevation above sea level 300 m is 1.15 kg/m^3. This is very low in comparison with fibers density (from 900 till 1600 kg/m^3) and the eqn. (12) can be simplified

$$\rho_T = \frac{W}{H} \approx \rho_F v_F \ and\ v_F \approx \frac{\rho_T}{\rho_F} = \frac{W}{\rho_F H} \quad (13)$$

Low planar mass and high thickness leads to the portion of fibers below 5 % i.e. porosity is over 95%. This is main reason why the total thermal conductivity is governed by porosity or volume portion of fibrous phase and not by conductivity of fibers.

For obtaining sufficient thermal insulation it is necessary to create material with the same porosity but much higher thickness.

The minimum thickness of highest insulating textile layer (with the same thermal conductivity as air) ensuring chosen *clo* is shown in (Figure 14).

It can be calculated, that for thickness *H* under 2 mm is magnitude of thermal insulation in *clo* units very low even for materials with thermal conductivity on the level of air (λ_a = 0.024 [W m^{-1}K^{-1}]).

For effective thermal insulation especially at low temperatures it should be selected *sufficiently high thickness* of textile layer. One possibility is to use as starting lap high insulation layer and create thicker product by ROTIS technology.

For comparative purposes the insulation layers from the three samples were prepared:

Sample1 -*Polartec alpha* (PES multifil, PES staple, PES/VS multifil)

Sample2 - two layers composed from PP 1.5 dtex nonwoven web covered by Polartec alpha and perpendicularly laid by ROTIS technology

Sample3-three layers composed from Polartec alpha covered from both sides by PP 1.5 dtex nonwoven web and perpendicularly laid by ROTIS technology (Figure 15)

Different comfort related properties of these samples are summarized in (Figure 16).

It is visible, that thermal resistance of three-layer structure is approximately two times higher in comparison with single Polartec structure.

Conclusion

This article presents possibilities of application of surface fixation by quasi-yarns technology in:

- Nonwoven structure fixation of conventional products and of non-conventional products;

Figure 15: Three-layer ROTIS with Polartec alpha in center.

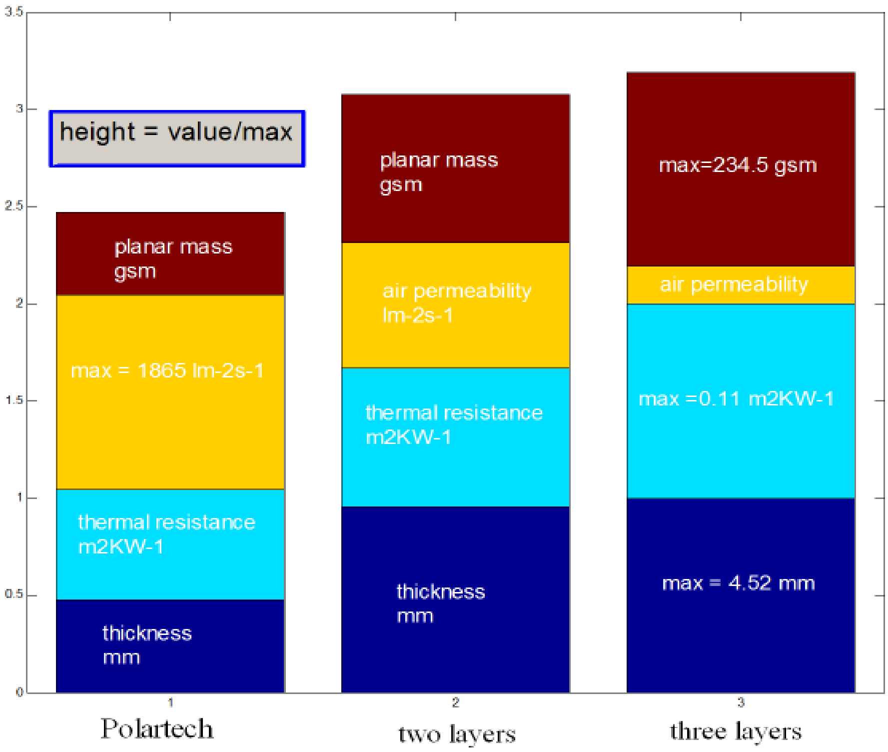

Figure 16: Selected properties of multilayer high insulation samples.

- Laminating of nonwoven products both conventional and non-conventional products;

Non-conventional products are expected to bring:

- More convenient pressure redistribution in case of their application in mattresses;
- Unusual look in case of non-technical applications.

Technology of nonwoven structures fixation by quasi-yarn is expected to bring:

- Material savings in case of technical applications;
- Energy savings;

It is known that the required total thermal insulation depends on human physical activities as. In the case of lowest activities is clo for outside temperature -20°C equal approximately to 6. For this thermal insulation *clo* value even material with air thermal conductivity should have thickness over 2.5 cm.

In cold conditions the wind will be very important for comfort prediction. Instead of wind chilly index it is possible to calculate convective heat transfer for comfortable skin temperature [9].

By ROTIS technology is then relatively simple to combine multiple layers into compact structure with required total thermal insulation for extreme condition (as polar clothing). It is possible to add the thin metallic foil with needle punched voids for reflecting thermal radiation back to human body etc. Therefore, ROTIS combined with quasi-yarns is versatile technology replacing effectively standard multi layering.

Acknowledgments

This study was supported by the project "Modular platform for autonomous chassis of specified electric vehicles for freight and equipment transportation", Reg. No. CZ.02.1.01/0.0/0.0/16_025/0007293 and the project of Ministry of Education, Youth, and Sports of the Czech Republic and the European Union-European Structural and Investment Funds in the Frames of Operational Programme Research, Development and Education-project Hybrid Materials for Hierarchical Structures (HyHi, Reg. No. CZ.02.1.01/0.0/0.0/16_019/0000843).

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