Thermal comfort of diving dry suit with the use of the warp-knitted fabric

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Abstract. Achievement of a good level of thermal comfort of under-suits for dry suit diving which enable also the required mobility of the diver in water is inevitable not only for the scuba sport and commercial diving people but also for safety and activities of people who make research under water. The aim of this work is to verify whether selected knitted structures (which are not waterproof) can substitute the currently used textile materials (nonwovens). This dry-suit innovation is intended to increase the properties which correspond to the perception of thermal comfort of the diver in water. To achieve this objective, the Alambeta thermal tester was used in the study for experimental determination of thermal resistance of spacer warp knitted fabric at varying contact pressure. The studied textiles were expected to be very suitable for the intended application due to their low compressibility which yields relatively high thickness a hence increased thermal insulation.

1. Introduction

A Spacer fabric is a double-faced fabric knitted on a double needle bar machine. The distance between the two surfaces is retained after compression by the resilience of the pile yarn (usually mono-filament) that passes between them. End-used for spacer fabrics include moulded bra cups, padding, and linings. Other applications are being investigated [1].

To analyse the effect of fabric thermal properties under high value of pressure, it should be noted that a spacer knitted fabric has a different mechanical behaviour in different directions. The various constructions between the wale-wise and course-wise directions can cause different fabric compression behaviour due to the various number of contacting points. In addition, during compression the spacer monofilaments into the structure can contact one another [2].

It is necessary to point out that the compression resistance of spacer fabrics increases with decreasing the inclination of the spacer yarns, because the spacer yarns with lower inclination are more oriented to the direction of the impact. This can be easily understood by referring to the theory of elastic stability from which the critical load P_{cr} of an elastic rod is given by the following equations:

when the two ends of the elastic rod are pinned: Firstly,

$$P_{cr} = \frac{\pi^2 EI}{l^2} \tag{1}$$

And secondly, when the two ends are fixed:

$$P_{cr} = \frac{4\pi^2 EI}{l^2} \tag{2}$$

Where E is the module of elasticity of the material, I is the moment of inertia of the cross-sectional area of the rod, and l is the length of the elastic rod. From Equations (1) and (2), it is easily shown that the shorter elastic rod exhibits the higher critical load, which leads to higher compression resistance. Therefore, the fabric with lower angle of inclination will have higher compression resistance [3].
With increasing the fabric thickness, the spacer yarns get longer. If considering the spacer yarns as slender rods, their compression resistance will decrease with increasing their length, as indicated by Equations (1) and (2).

2. Thermal properties of textiles

Thermal comfort properties of textile materials have gained the attention of researchers in recent times. Although a plethora of researches have been conducted on the mechanical properties of textile fabrics, they have hardly played any role during the actual use of the fabrics. In contrast, comfort properties determine the way in which the heat, air and water vapour are transmitted across the fabric. During heavy activities, the body produces lots of heat energy and the body temperature rises. To reduce the temperature, the body perspires in liquid and vapour form. When this perspiration is evaporated to atmosphere, the body temperature reduces.

2.1Principle of ALAMBETA instrument – fabric thermal properties tester

This apparatus used in this study enables the measurement of the following thermal parameters: thermal conductivity, thermal absorbtivity, thermal resistance and sample thickness. The Alambeta simulates the dry human skin and its principle depends in mathematical processing of time course of heat flow passing through the tested fabric due to different temperatures of bottom measuring plate (22°C) and measuring head (32°C). When the specimen is inserted, the measuring head drops down, touches the fabrics and the heat flow levels are processed in the computer and thermo-physical properties of the measured specimen are evaluated [4].
Thermal properties of textiles such as the thermal resistance, thermal conductivity and thermal absorbtivity are influenced by the yarn composition and structure, fabric structure, density, humidity, type of textile construction, surface treatment, filling and compressibility, air permeability, surrounding temperature and other factors. Thermal conductivity coefficient λ presents the amount of heat, which passes from $1m^2$ area of material through the distance 1 m within 1 s and creates the temperature difference 1 K. The highest thermal conductivity exhibit metals, whereas polymers have low thermal conductivity, ranging from 0,2 to 0,4 W/m/K.
Thermal conductivity of textile structures generally reaches levels from 0,033 to 0,01 W/m/K. Thermal absorbtivity b of fabrics was introduced by Hes [4] to characterise thermal feeling (heat flow level) during short contact of human skin with the fabric surface. Providing that the time of heat contact τ between the human skin and the textile is shorter than several seconds, the measured fabric can be simplified into semi-infinite homogenous mass with certain thermal capacity ρc (J/m^3) and initial temperature t^2. The higher is thermal absorbtivity of the fabric; the cooler is its feeling. In the textile praxis, this parameter ranges from 20 $Ws^{1/2}/m^2$ /K for fine nonwoven webs to 600 $Ws^{1/2}/m^2$ /K for heavy wet fabrics. Thermal resistance R (m^2K/W) depends on fabric thickness h and thermal conductivity λ, i.e. the equation is given by relation:

$$R = h/\lambda \quad (3)$$

3. Experimental results

Three types of the dive dry-suits (NW – 1, 2, 3, 3 – used) were used for non-destructive method of ALAMBETA testing. The basic characteristic parameters of these nonwoven structures were not found. It was not possible to cut the real suit for studying.
For the comparison, thermal parameters of the non-used dive-dry suit and dry-suit after 300 scuba dives were evaluated (NW – 3, 3 – used). Afterwards, 6 different warp-knitted spacer fabrics and 4 types of nonwoven fabrics were experimentally evaluated under laboratory conditions (t = 23 °C and φ = 48 %).

3.1Testing of the real dive dry-suits

The first results of the ALAMBETA instrument are given in the Table 1 add in the Figures 1 – 3.

Table 1. Thermal parameters of the evaluated dive-dry suits

	h (mm)	10^3 λ (W/mK)	10^3 *R* (m².K/W)	*q* (W/m²)	*b* (Wm^{-2}.s$^{1/2}$.K^{-1})
NW - 1	6.64	41.6	159	0.119	57.8
NW - 2	12.4	49.4	250	0.178	55
NW - 3	11.5	41.8	275	0.126	39.4
NW - 3 (used)	8.65	40.6	213	0.158	48.5

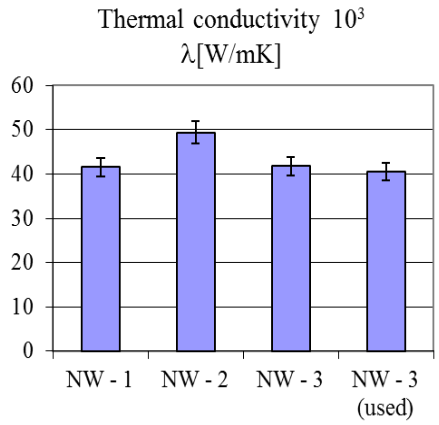


Figure 1. Thermal conductivity of the dive dry-suit

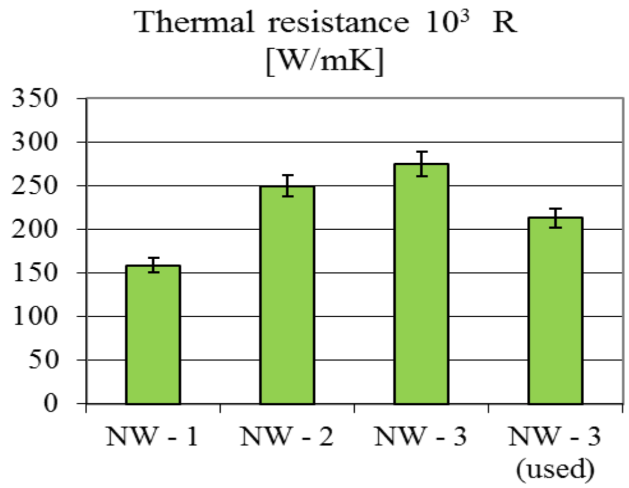


Figure 2. Thermal resistance of the dive dry-suit

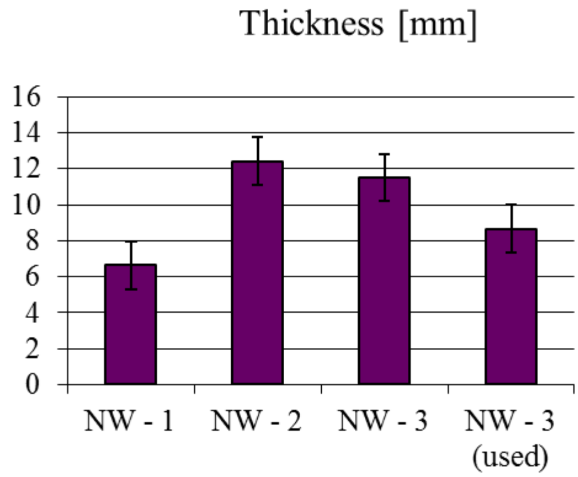


Figure 3. Thickness of the dive dry-suit (ALAMBETA)

Thermal conductivity values of all dry-suits exhibited low variability, in respect of their confidence interval (Figure 1). The personal experience of the scuba divers refers to the use of the suit named NW – 3. They consider that dry-suit as more comfortable. The determined thermal resistance levels correspond to the thickness of the suits (Figures 2, 3). The structure of these dry-suits was not analysed in order to avoid their destruction.
Repeated diving cycles bring the decrease of thermal resistance of the suits, as it depends on the fabric thickness. The biggest drop of the thickness of the used dry-suits is the main reason why this suit is not comfortable for diving in cold water. The water pressure during the diving brings about the changes of the nonwoven structure.

3.2 Testing of the cut samples of innovative dry-suit by mans of the ALAMBETA instrument

In the experiment five structures of dry-suit materials were compared (Table 2), four based on conventional nonwovens (now used and produced) and one with the innovative warp-knitted spacer layer (Figure 4). Samples consist from:

- Outer layer – woven fabric
- Middle layer – nonwoven fabric or warp-knitted spacer fabric
- Inner layer – warp knit or weft knit (in the case of warp-knitted spacer the inner layer was not necessary)

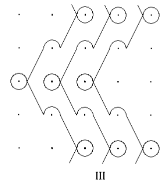


Figure. 4 Notation of the spacer monofilament (GB 3 and 4), PL 76 tex f 24, PL 33 f1.

Table 2. Thermal comfort properties of all studied dry-suits. (The values of individual suits were determined under the pressure 200 and 1000 Pascal).

Type of used material for simulation of the dry-suits	10^3 λ (W/mK)	10^3 R (m².K/W)	q (W/m.m)	b (Wm^{-2}. s$^{1/2}$.K^{-1})	h (mm)
1=Woven/Nonwoven (hollow fibre) 150 g/m^2/Warp knit	50.1	253	0.086	17	12.7
1- 1000 Pa	38.2	124	0.127	30.1	4.74
2=Woven/Nonwoven (hollow fibre +Ag) 150 g/m^2/Warp	47.9	327	0.053	15	15.7
2- 1000 Pa	38.5	192	0.076	18.7	7.41
3=Woven/Nonwoven (hollow fibre) 150 g/m^2/Weft knit	46.7	227	0.093	19	10.6
3- 1000 Pa	37.4	124	0.114	31.9	4.63
4=Woven/Nonwoven (profile fibre) 300 g/m^2/Warp knit	49.3	404	0.024	5.9	19.9
4- 1000 Pa	40.4	215	0.033	11.8	8.69
5=Woven/Warp-knited spacer	49.9	76.2	0.302	58.8	3.8
5- 1000 Pa	47.7	73.2	0.328	63.9	3.49

The measurement was performed under the two pressure levels which are possible to set in the ALAMBETA tester. The confidence interval of thermal conductivity and thickness (10 samples) was also determined; see the Figure 5, 6.

Unfortunately, better thermal properties did not result from the use of multiple layers of nonwoven fabrics (see the results of samples No. 4). The disadvantage of the increasing the mass of the dry-suits will be higher than the advantage of the comfort benefit.

As expected, under the increasing pressure the thickness of the spacer fabric decreases – see the sample 5. However, thermal resistance of the warp spacer knits suits less decreases under high pressure then thermal resistance of the suits made of nonwoven fabrics including fabrics with special hollow fibres.

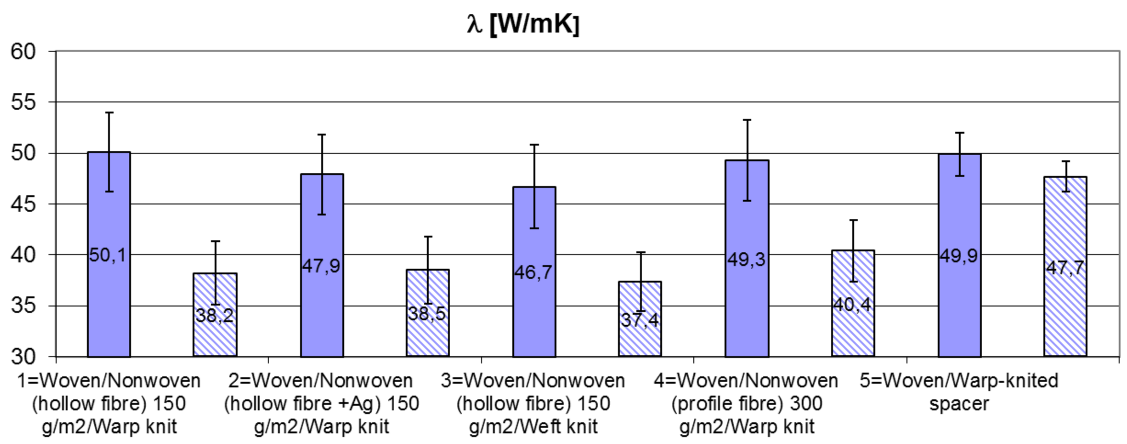
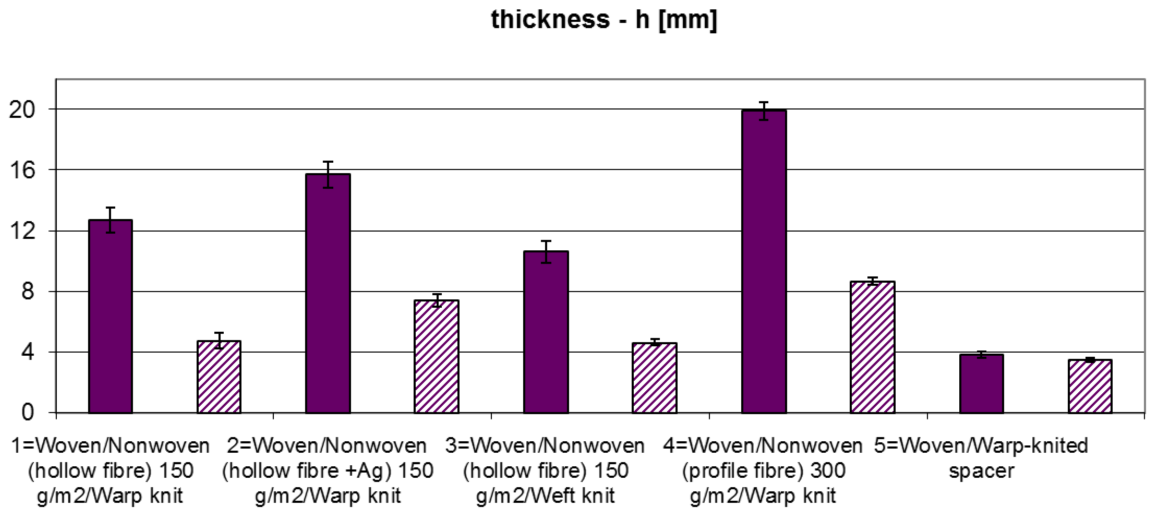


Figure 5. Thermal conductivity of the cut samples – two levels of pressure



200 Pa 1000 Pa 200 Pa 1000 Pa 200 Pa 1000 Pa 200 Pa 1000 Pa

Figure 6. Thickness of the cut samples (ALAMBETA) – two levels of pressure

3.3 Measurement of the inclination spacer fibres of warp-knits – CT scanner

Warp-knitted spacer fabrics are often used for improvement of the compression behaviour which is depends on the three layer structure configuration (lapping), on the spacer materials (monofilament diameter) and on the stitch density of two layers (outer). Thanks to their small inclination at the fabric compression these materials enable certain air flow inside the fabric and cause certain thermal comfort, which depends on the thickness during the contact pressure that is on the compression resistance.

To determine the real value of the inclination of the spacer fibres inside the warp-knitted fabric and the impact of the fixation process on the change of the monofilament inclination (the samples thickness has to be changed too) the experiment with CT scanner was performed.

CT scanner uses an x-ray source with adjustable voltage and a range of filters for versatile adaptation to different object densities. Internal structures are reconstructed as a series of 2D cross sections (Figure 7) which are then used to analyse the two and three dimensional morphological parameters of the object. The process is non-destructive [5].

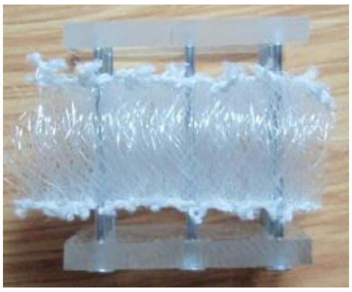


Figure 7. Apparatus for micro CT-scanner SkyScan 1174

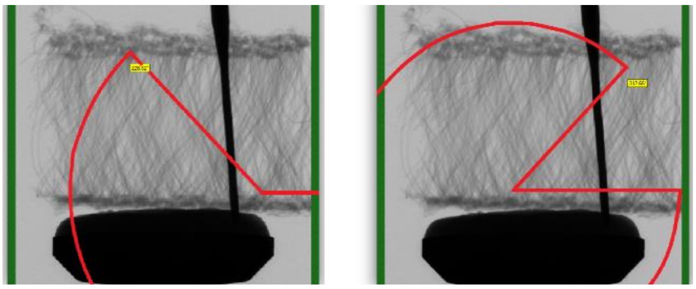


Figure 8. Measurement of the spacer monofil angles

This process starts by the approximation of one of the monofilaments and then by approximation of another monofilament, which crosses the first one. Two angles are then determined and after subtraction the real inclination of two monofilament axes are calculated. Statistical data of the angles from the three samples (thirty values) are given in the Table 3.

Table 3. Inclinations of the monofilaments axes from the spacer warp-knitted fabric surface [6].

	Before fixation	After fixation
α (°)	58.8	91.8
s (°)	8.16	66.66
s^2 (°)	66.6	44.3
v (%)	13.8	7.25
Confidence (°)	55.7-61.8	89.3-94.3

If the angle of two monofilaments is high (after fixation), the resistance to compression of these structure is lower. The process of fixation changes the structural parameters and these changes increase the pressure resistance. Higher monofilament angle predicts a structure with higher compressibility. The other characteristics which affect the compressibility of spacer fabrics are density of spacer warp-knitted fabric, type and count of spacer fibres and lapping diagram together with the thickness of the fabric, which is given by the needle bed distance of the double needle bar raschel machine.

The structure of the double needle bar warp-knitted filet in its cross section is given by the lapping diagram of the monofilaments. During the fabric production and before fixation process the monofilament angle is in the non-relaxed state and the fabric mechanical characteristics (which depend on the thickness and compressibility) can differ in values.

3.4 Innovation of the dive dry-suit with the spacer knits

As follows from the Tab. 4, thermal resistance of the warp spacer knits suits under high pressures practically did not change, contrary to the thermal resistance of the suits made of nonwoven fabrics including fabrics with special hollow fibres, which dropped substantively.

This resistance against pressure of the suit based on spacer fabric is caused by high compression resistance of the middle layer. The inclination of the spacer monofilament fibres brings this stability.

Some characteristics and results of the thickness testing especially of the spacer knits are given in the Table 4. It is probably the first attempt to describe the thermal comfort of the spacer fabrics. The samples differ in their thickness (and therefore the materials for spacer layer differ too). The notation of these structures varies and the threading of the guide bar too.

During the samples compression the yarn geometry changes and fabric structure is temporarily or permanently disrupted. Owing to this process the thermal resistance decreases. The compression level Z can be determined by the relation and may also be formatted as

$$Z = \frac{h_1 - h_2}{log\ p_2 - log\ p_1} \tag{4}$$

where h_1 (mm) is thickness under the pressure p_1 (Pa) and h_2 (mm) is thickness under the pressure p_2 (Pa). These values were determined with UNI-THICK instrument.

Table 4. Characteristics of the tested materials

	Material	Thickness	Square mass	Thickness difference Δh (%) under pressure		
		(mm)	(gm^{-2})	(200 - 1000) (Pa)	(1000 - 10000) (Pa)	(10000 - 100000) (Pa)
Spacer A	PL 83 tex, f180; PL 0.25mm	10	500	5.37	45.44	80.22
Spacer B	PL 7.6 tex, f 24; PL 0.09 mm	6	300	4.5	33.45	81.47
Spacer C	PL 83 tex, f180; PL 0.25mm	6	335	5.3	39.1	77.8
Spacer D	PL 83 tex, f180; PL 0.25mm	7	490	3.94	23.7	69.93
Spacer E	PL 83 tex, f180; PL 0.25mm	10	850	6.78	20.59	65.93
Spacer F	PL 83 tex, f180; PL 0.25mm	10	800	5.64	16.37	63.18
Nonwoven	PL	18.87	54.09	18.87	54.09	87.13

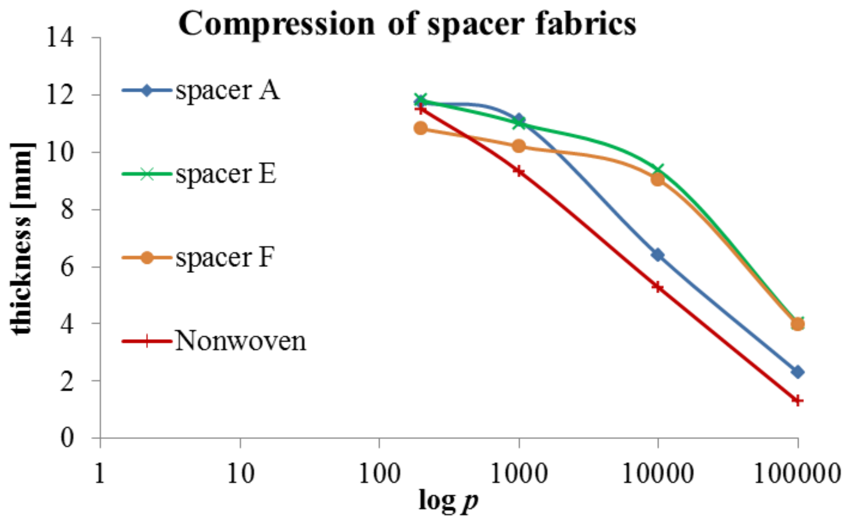


Figure 9. The thickness influence of warp-knitted spacer fabrics and nonwoven

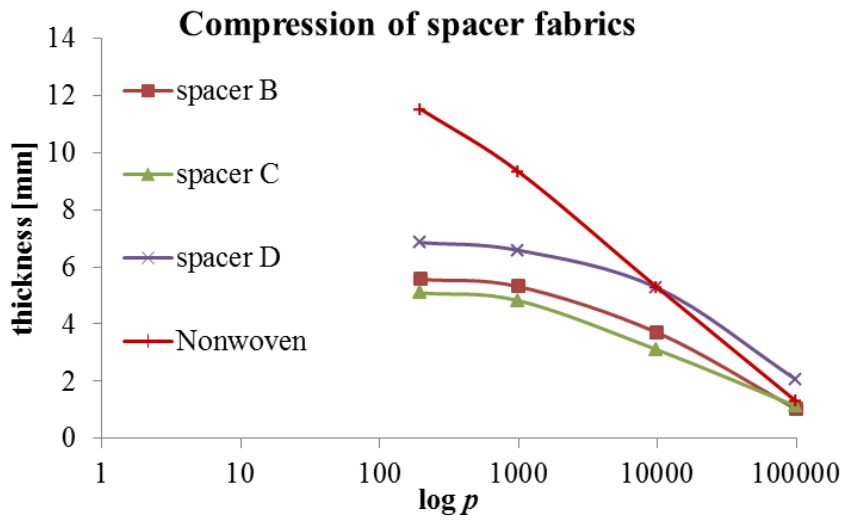


Figure 10. The effect of pressure on the thickness of warp-knitted spacer fabrics and nonwovens

The Figure 10 clearly illustrates the thickness changes. Thermal conductivity, thermal resistance and thermal absorptivity depend on the changed volume density (porosity) of the samples.

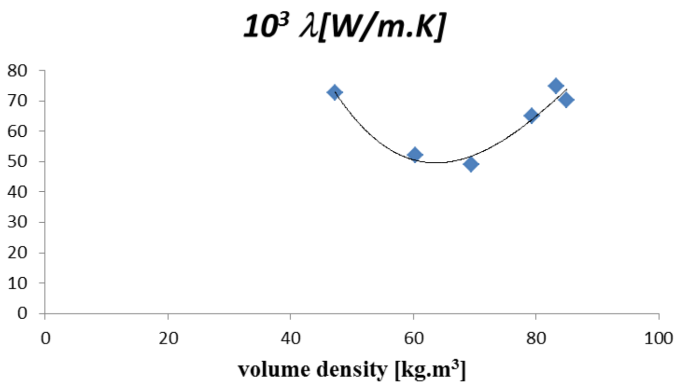


Figure 11. Thermal conductivity of spacer knits and nonwovens

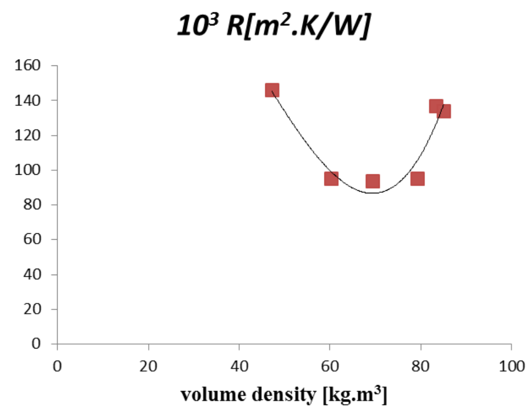


Figure 12. Thermal resistance of the spacer knits and nonwovens

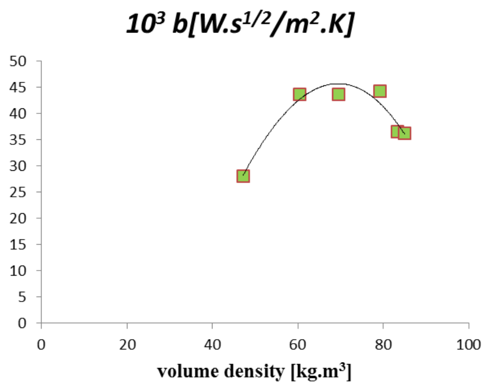


Figure 13. Thermal absorptivity of spacer knits and nonwovens

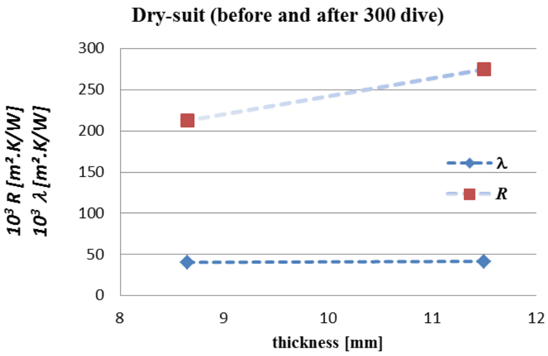


Figure 14. Comparison of properties a new and used dive dry-suit with nonwovens (influence of water pressure)

4. Results and discussion

The increasing water pressure during the scuba diving influences the structure of dry-suits and changes their thermal properties, as can be seen in the Figure 14.

From the above results follow, that this sort of suits can really offer the expected high level of thermal insulation by maintaining an air (or special gas) layer between the body and the cold water. On the other hand, it features certain disadvantage resulting from higher bending and shearing stiffness, which may reduce the mobility of the diver under water. This disadvantage can be not so inconvenient due to the position in the water – trim.

The advantages of the innovative dry-suit with spacer warp knitted fabric are:

- better thermal properties which are necessary for scuba-diver comfort under cold water
- due to the pressure resistant the thickness of the suit will not be changed after diver cycles.

Contrary to these benefits the disadvantages with using spacer knits are:

- smaller un-comfortableness in “swimming” (stiffness of the knitted textiles)
- problems with diving down owing to huge volume of the air into the structure
- difficulty in processing of spacer fabric into a dive-dry suit.

5. References

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