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Thermodynamic qualification of knitted spacer fabrics for use as insulation box insert in the context of refrigerated transport containers in the logistics sector

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ABSTRACT

Temperature-sensitive products such as refrigerated and frozen goods pose particular challenges for logistics. Against the background of the mobility shift towards electric vehicles and the current challenges of temperature-stable transport in the field of pharmaceutical, esp. vaccine logistics in the context of the SARS-CoV-2 pandemic, new, energy-efficient vehicle equipment is needed to maintain cold chains. Known refrigeration concepts are designed to cool the entire cargo hold. In addition, the goods cannot be removed from the vehicle while maintaining the cold chain. An insulating effect of containers is typically achieved by using foamed polystyrene (Styrofoam). On the one hand, these structures have a very good insulating effect, but on the other hand, they cannot be reduced in volume during recirculation and are problematic with regard to recycling. The aim of the research presented here is therefore to develop a knitted box that is designed as a volume-reducible, rigid but foldable box. This can be used as a supplement to existing transport container systems and therefore can be inserted in the transport container. The knitted box performs as insulation when the transported goods are actively cooled inside the box, which is more sustainable and flexible than recent insulation solutions. Knitted fabrics, especially spacer fabrics, have advantageous thermo-physical properties for this application due to their structural design. In the course of a research project, various spacer fabrics were tested for their thermo-physical suitability as insulation materials. It was found that knitted predetermined folding lines represent an insulation gap. Based on this, a new structure was developed which, due to its structural design, compensates for cold or thermal bridges at vertices and edges of the box. The results show that the knitted corrugated structure insulates better than the knitted spacer fabrics with predetermined folding lines. A thermal imaging camera was used to identify critical points for heat transfer.

Keywords
knitted spacer fabric,
structural design,
transport container,
volume-reducible box,
knitted box,
logistics,
insulation,
active cooling,
insulating insert

1 Introduction

Compared to other materials, textile constructions are characterized by the large proportion of air spaces. The air volume and the distribution of the air space influence the properties of the textile, particularly with regard to its slope of passage and thus its insulating effect [1]. Due to their structural design, knitted fabrics have a particularly large void volume, which gives them advantageous properties for a wide range of applications [2]. The final application of knitted textiles depends in many cases on their thermo-physical properties. These result essentially from their geometric properties rather than from the fiber material. Depending on the type of material, textile fibers have a thermal conductivity 10 to 20 times higher than air (wool 0.186, cotton 0.291, polyamide 0.233, polyester 0.174, polyacrylic 0.174, air 0.026 W/(m K). Therefore, the insulating effect of textiles is not originated from the fiber only, but rather from the textile's ability to trap and hold air. Textiles act as a kind of carrier material that creates air volume and enables the formation of insulating adhesive air layers on each fiber surface. Ideally, the enclosed air must be kept at rest so that there is no exchange of air with the environment and thus no convective heat transport. Accordingly, textile constructions that have relatively few fibers with a high volume, i.e., large thickness, are particularly suitable for insulation [3,4]. Air exchange between textile and environment should be minimized even if the textile is compressed in its form. Thus, for an optimal insulating effect, the textile structure needs sufficient stability to resist compression and thus keep the insulation values stable over the surface. Due to their structural design, knitted fabrics, especially knitted spacer fabrics, are particularly suitable for this purpose [3]. Spacer knits consist of two parallel textile cover surfaces and at least one spacer thread system. The spacer thread (pile thread) connects the cover surfaces and at the same time keeps them apart at a distance. This three-dimensional structure distinguishes spacer textiles from flat textiles in terms of their properties [5,6]. Knitted textiles have a favorable ratio between material and void or air volume. Their structure favors the inclusion of air, which makes the textile more transmission-resistant and thus more insulating. At the same time, however, knitted fabrics have a porous surface due to their mesh structure. Since each stitch represents a hole in the textile surface, the nature and arrangement of the stitches influence the ratio of the void volume to the total volume, i.e. the porosity of the fabric, and thus its permeability [7]. The structure design thus has a significant influence on the thermal resistance and thus the insulation effect.

In the research project presented here, a textile box insert is being developed in the shape of a form-fitting, foldable spacer knit, which upgrades the standard logistics container to an insulating box in the sense of a box-in-box system (cf. Figure 1). The transport container thus acts purely as a carrier without any specific insulating effect. Moreover, the box-in-box construct does not contain any other active technology. Rather, it is coupled to an external cooling system by insertion into a racking system (e.g. in a delivery vehicle). Thus, instead of the usual non-directional cooling of the entire cargo space, individual cooling is realized for each box. This allows the interior volume of the box to be tempered in a targeted and product-specific manner. When the container is actively cooled, the spacer fabric takes on the function of an insulating layer and must therefore have stable insulation values over the entire textile surface. The structural design of the spacer fabric offers the possibility of achieving an optimum balance between insulation and shape adaptation. A key challenge is to avoid the high convection, which is present in the textile spacer fabric (0.08-0.1 W/(m K) on average) in the insulating layer, as well as to prevent potential thermal or cold bridges at edge areas such as vertices and edges [8].

2 Materials and methods

2.1 Knitted fabrics

Spacer knits were produced by the company Hero-Textil AG on a CMS 433.6 flat knitting machine from Stoll (gauge E12) using a 167 dtex polyester yarn, an elastane yarn (cover surfaces) and a textured polyester yarn (Diolen®High Volume, pile thread). The insulation capacity of the knitted fabrics is recorded and evaluated in comparison with a reference sample made of polystyrene on the basis of two measurement methods. Polystyrene has an approximate thermal conductivity λ of 0.05 W/(m K) (cf. Table 1) and is often used as standard for insulating transport containers.

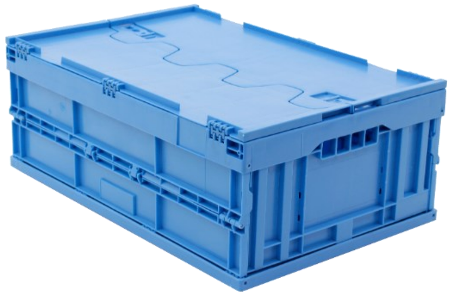

Figure 1. Standard logistics container from the Walther Faltsysteme GmbH to be upgraded by using a knitted insulating box insert [9].

Table 1. Test results reference sample polystyrene, m = 5.*

	Areal weight in g/m^2	Thickness in mm	λ in W/(m K)
max	242.5	6.23	0.051
min	240.6	6.12	0.049
Av*	**244.3**	**6.17**	**0.049**
SD	3.1	0.05	0.001

*m = number of measurement repetitions, av = average, SD = standard deviation

The knitted spacer fabrics were adjusted according to ISO 139 in a standard climate. Five comparative tests were carried out (exception: see Table 5), from which an average value was calculated. The tests were performed by Niederrhein University of Applied Sciences and Steinbeis-Innovationszentrum Energie- und Umwelttechnik. The sample thickness was determined by using the Frank-PTI thickness tester in accordance with DIN EN ISO 5084. In order to achieve the closest possible approximation to the actual knitted fabric thickness in the unloaded state, the measurements for thickness determination were carried out in accordance with Chung et al. [10] with a compressive load of 0.1 kPa and not 1 kPa as specified in the standard. The samples are loaded on a test surface of 20 cm^2 for 30 seconds per measurement [11]. The areal weight was tested following EN ISO 12127 [12].

2.2 Thermal Conductivity

The insulation effect of the specimens was checked by means of two methods. Firstly, the thermal resistance was determined by means of the sweating guarded-hotplate test on the Permetest tester (2009 version) following ISO 11092. For the measurement, a constant temperature difference between the heating element and the flowing air (1.00 m/s ± 0.05 m/s) is generated, with the heating element constantly controlled to an air temperature of +10 K. The thermocouples in the measuring unit measure the heat flow that occurs when a specimen is inserted. The thermocouples output a voltage U as a function of temperature. The change in voltage of the thermocouple from state 0 (without sample) to state S (with sample) is linearly proportional to the change in thermal resistance, i.e. the thermal resistance of the sample. The thermal resistance R_t is given as the temperature difference between the two surfaces of the sample $(T_m - T_a)$ in K per specified area A in m^2 (area of the measuring head) divided by the resulting heat flux H in W and the correction factor ΔH_c and can thus be determined from the following formula:

Thermal resistance in m²miliK/W $$R_t = \frac{(T_m - T_a)\cdot A}{H - \Delta H_c} \quad (1)$$

Multiplying the inverse thermal resistance ($1/R_t$) by the layer thickness of the sample in m gives the thermal conductivity λ of the material in W/(m K).

The thickness of the sample is limited to 7 mm, since beyond that measurement errors due to heat loss at the edges of the sample cannot be excluded [13-15]. For this reason, the samples were subjected to a second test procedure, which allows the testing of samples with larger thicknesses.

The thermal conductivity was therefore also measured in accordance with DIN 52616 using a heat flow plate apparatus. The specimen is placed between a heating and a cooling plate. A temperature gradient is established, resulting in a heat flow through the specimen. The heat flow measuring plate, which is located between the heating or cooling plate and the sample, consists of a large number (500 - 1000) of thermocouples connected in series (thermocouple chain). These are thermally separated by an insulating medium. Thus, according to the temperature difference between the upper and lower side of the plate, a voltage is output. This is directly proportional to the heat flow through the plate in the measuring range. Thus, the heat flow through the plate and thus through the sample can be determined. To minimize measurement errors, measurements are taken on the top and bottom of the specimen in each case and these values are averaged [16,17].

Heat flux density in W/m² $$q = \frac{(\dot{q}_w + \dot{q}_k)}{2} \quad (2)$$

Thermal conductivity in W/(m K) $$\lambda = \frac{\dot{q}\cdot s}{t_w - t_k} \quad (3)$$

The insulation effect of the samples was also recorded and evaluated visually using the thermal imaging camera Variocam HD by Jenoptik (emissivity of 0.95 for PE and PP).

3 Testing results

3.1 Thermal conductivity – Permetest tester

First, samples A1, A2 and A3 were taken from a box knitted to shape (cf. Figure 2, 3). Samples A2 and A3 are surfaces that contain predetermined folding lines, i.e. they were taken from the edge area of the box. Sample A1 does not contain a predetermined folding line. The samples were tested for thermal conductivity using the Permetest tester.

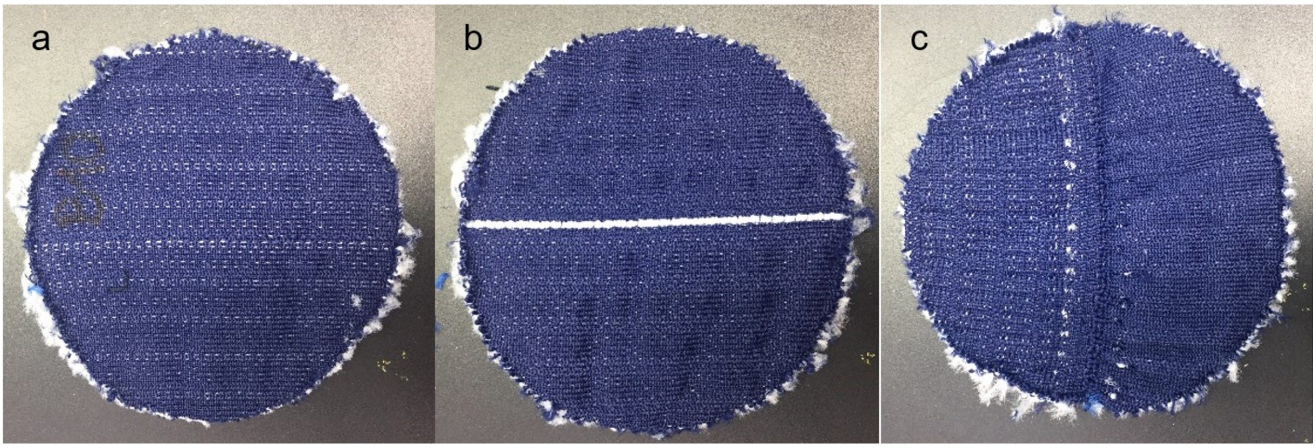

Figure 2. (a) Specimen A1 without predetermined folding line, (b) specimen A2 with predetermined folding line as concrete horizontal knitted course, (c) specimen A3 with predetermined folding line as vertical three-dimensional structure.

Figure 3. Specimen A1-A3 cross-section.

Table 2. Testing results (Permetest) for pattern A1 without predetermined folding line, m = 5.

	NoW/cm*	NoR/cm*	Areal weight in g/m²	Thickness in mm	λ in W/(m K)
max	7.5	13	1023.24	6.32	0.099
min	7	12	988.4	5.66	0.056
av	**7.1**	**12.5**	**1004.34**	**5.95**	**0.079**
SD	0.22	0.35	13.06	0.26	0.018

*Number of wales, number of rows

Table 3. Testing results (Permetest) for pattern A2 with predetermined folding line, m = 5.

	NoW/cm	NoR/cm	Areal weight in g/m²	Thickness in mm	λ in W/(m K)
max			1023.7	7.31	0.218
min			969.73	6.71	0.121
av	**7**	**12**	**1003.12**	**6.94**	**0.174**
SD	0	0	22.48	0.28	0.036

Table 4. Testing results (Permetest) for pattern A3 with predetermined folding line, m = 5.

	NoW/cm	NoR/cm	Areal weight in g/m²	Thickness in mm	λ in W/(m K)
max		11	1083.11	7.47	0.145
min		8.5	963.49	6.61	0.093
av	**8**	**10.1**	**1014.61**	**6.04**	**0.121**
SD	0	1.25	44.31	0.34	0.020

The test results show that the predetermined folding lines in samples A2 and A3 effect the insulation of the spacer fabric. Both samples A2 (0.17 W/(m K)) and A3 (0.12 W/(m K)) have a significantly higher thermal conductivity value than the comparison sample A1 (0.08 W/(m K)), which does not contain any predetermined folding lines (cf. Tables 2-4).

It can be concluded that the insulation effect decreases in the vertices and edge areas of the box compared to the flat wall areas of the box. Energy loss at these critical points must be prevented. For this reason, a corrugated knitted spacer structure was developed (further referred to as pattern B).

3.2 Thermal conductivity – heat flow plate apparatus

Since sample B (see Figure 4) has an average thickness of 11.44 mm, the further tests were carried out on a different testing device (heat flow plate apparatus). Sample A1, without predetermined folding lines, was also tested again on this apparatus for optimal comparison. To better capture the effect of the structure, sample B was tested once in the "relaxed" state and once in the "compressed" state. The compressed state is intended to simulate the application case (cf. Figure 6), when the waves collide in the edge region of the box. It is assumed that the compression provides better sealing and thus reduces the thermal conductivity.

Figure 4. Specimen B corrugated knitted spacer structure.

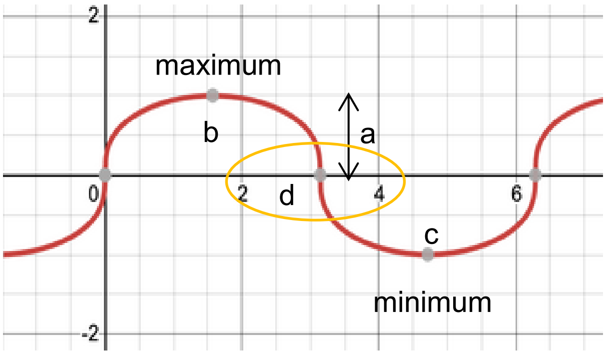

Figure 5. The structure of pattern B shows similarities to a sine curve. The following terms are used to describe the wave-like structure: (a) amplitude, (b) upper corrugation, (c) lower corrugation, (d) transition area between upper and lower corrugation.

Figure 6. Pattern B, in the three-dimensional application the corrugated structure seals the corners of the box by compression (edge highlighted in red).

Table 5. Testing results (heat flow measuring plate apparatus) pattern B, the sample was inserted compressed and relaxed, m = 5, measurement of weight and thickness m = 3.

					compressed	***relaxed***
	NoW/cm	**NoR/cm**	**Areal weight in g/m²**	**Thickness in mm**	**λ in W/(m K)**	**λ in W/(m K)**
max			2098.6	11.55	0.096	0.091
min			1967	11.29	0.091	0.090
av	**5**	**8**	**2052.87**	**11.44**	**0.094**	**0.090**
SD	0	0	74.4	0.13	0.003	0.001

Table 6. Testing results (heat flow measuring plate apparatus) pattern A1, m = 5.

	NoW/cm	NoR/cm	Areal weight in g/m²	Thickness in mm	λ in W/(m K)
max	7.5	13	1023.24	6.32	0.079
min	7	12	988.4	5.66	0.075
av	**7.1**	**12.5**	**1004.34**	**5.95**	**0.077**
SD	0.22	0.35	13.06	0.26	0.001

The results show that the corrugated structure of pattern B has a similar insulating effect in the total area in the compressed state (0.09 W/(m K)) as in the relaxed state (0.09 W/(m K)) (cf. Table 5). At the same time, the compressed pattern B does not insulate better than pattern A1 (0.08 W/(m K)) (cf. Table 6), although it is almost twice as thick. In order to be able to better classify these results, the samples were again placed in the testing device and the heat flow through the textile surfaces was recorded by using a thermal imaging camera.

3.3 Thermal imaging camera

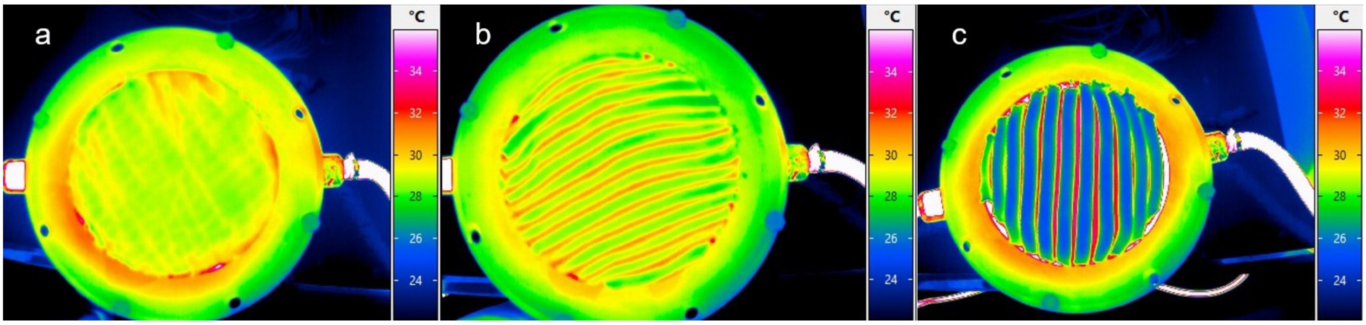

Figure 7. Specimen placed on the hot plate of the heat flow plate apparatus captured by a thermal imaging camera: a) A1, b) B compressed, c) B relaxed.

The thermal images show that structure A1 (cf. Figure 7a) has a relatively constant temperature of approx. 27-29 °C in the surface. Nevertheless, the structure design shows an effect on the insulation, so that there are temperature breakthroughs across the surface in the areas colored yellow and red toward the edges of the specimen. The average values present in the surface of pattern A1 correspond to the temperatures measured in the maximum of the amplitude of the corrugated structure of pattern B (cf. Figure 7b, 5). However, a tendency towards lower measured values of ≤ 27 °C is evident in the maximum of the wave with stronger compression (especially towards the edge region). Figure 7b also illustrates that heat breakthroughs occur in the areas of transition from the upper to the lower corrugation (cf. Figure 5). Here, temperatures in the range of 30-32 °C are measured. A comparison of Figures 7b and 7c illustrates that the transition region between the upper and lower corrugations favors heat loss in the relaxed state. Nevertheless, temperatures of approx. 26 °C are measured in the maximum amplitude, which represents a lower heat loss than in the compressed equivalent (compare figure 7c).

Figure 8 shows a comparison of the insulation performance of the tested samples. On the one hand, it can be seen that the patterns with predetermined folding lines (A2, A3) have lower isolation capability than the pattern without predetermined folding lines (A1). However, the high variance in the values caused by the test procedure with the Permetest device must be taken into account. The test method with the heat flow measuring apparatus brings a smaller scatter in the measured values. It can be seen that sample B in the compressed and relaxed state shows a slightly higher thermal conductivity value than sample A1. A1 is closest to the thermal conductivity of the polystyrene reference pattern of all the spacer structures tested.

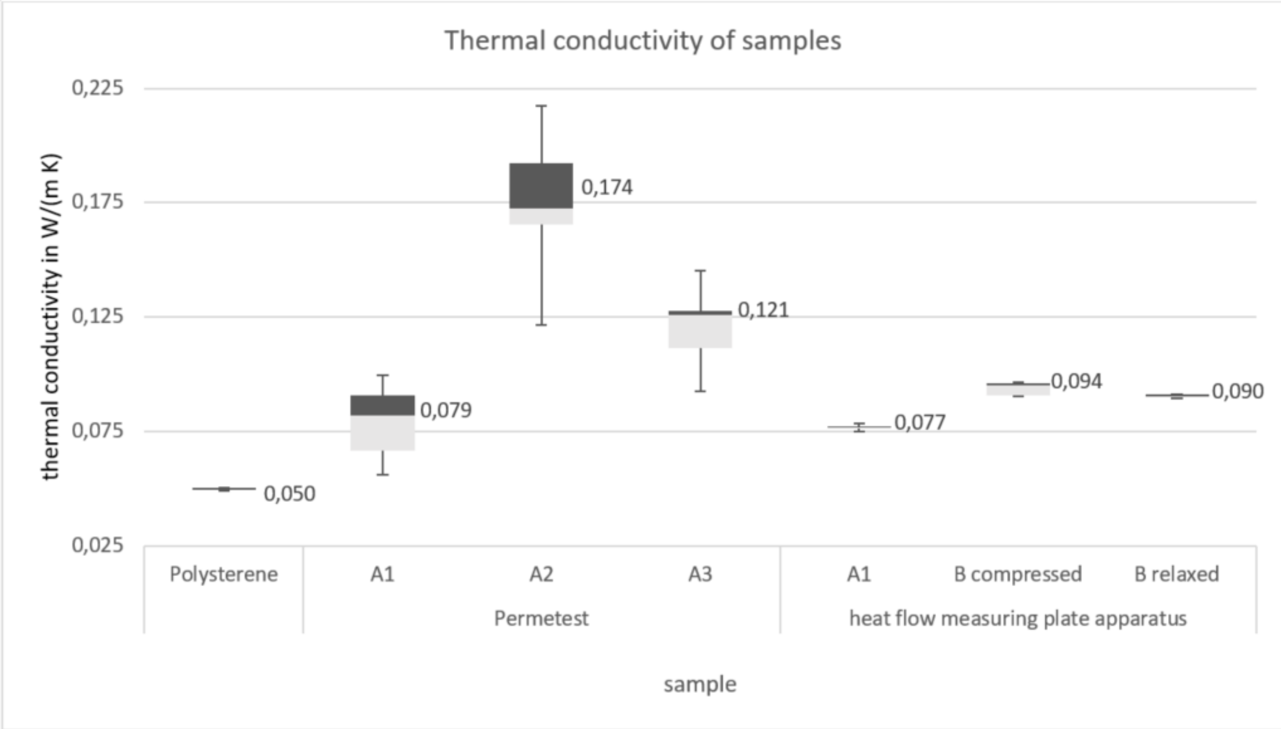

Figure 8. Comparison of the insulation capacity of the tested samples by test method, m = 5.

4 Conclusion and outlook

The spacer fabrics with predetermined folding lines show a significantly higher tendency to conduct thermal energy through the textile surface (sample A2: 0.17 W/(m K), sample A3: 0.12 W/(m K)) than sample A1 (0.08 W/(m K)) without predetermined folding lines and thus represent a weak point in the insulation. Pattern B has a corrugated structure that is designed to insulate the container edges when compressed in the edge areas. The results show that a better insulating effect can be achieved compared to the patterns with predetermined folding lines. However, pattern B still conducts more heat than pattern A1. The compressed state of the corrugated structure (0.09 W/(m K)) does not seem to improve the thermal conductivity compared to the relaxed state (0.09 W/(m K)). The thermal images show that in the maximum of the amplitude of the corrugated structure, the insulation effect is higher (but relaxed better than compressed) than for the planar structure of sample A1. However, the transition areas between the peaks and the valley of the corrugations represent significant thermal bridges. In the relaxed state, this effect is even more pronounced (>32 °C) than in the compressed state. It can be assumed that these thermal bridges compensates the comparatively good values in the maximum amplitude, and that structure B thus conducts more heat relative to the total area than structure A1 (A1 0.08 W/(m K), B 0.09 W/(m K)). Final, it cannot be said with certainty, whether the compressed state actually insulates better than the relaxed state, since the measured thermal conductivity values are approximately the same (0.09 W/(m K)). Compressing the structure does increase the tightness in the outer structure, however, the relaxed structure has a higher volume inside, allowing more air to be trapped and held in. Both effects, the tightness of the outer structure and the volume inside the spacer structure, need to be investigated further.

Based on these results, the corrugated structure of pattern B will be optimized. The critical points for insulation in the wave gaps are to be compensated. The maximum height of the corrugations will be adjusted to produce both a higher thickness (18 mm) and more fiber volume inside, which will promote air entrapment and improve insulation. In addition, the effect of a two-layer structure will be studied to produce a higher tightness. Apart from an investigation of the insulation effect of the textile structure, the functioning of the inlay in its three-dimensional form must be analyzed. Even if no insulation contribution of the logistics container is expected in the interaction of container and knitted fabric, it is necessary to investigate how the textile insulation insert behaves in the unfolded application state in the box. Further tests will be carried out for this purpose.

Author Contributions

J. Klausmann: writing – original draft preparation, analysis, investigation, conceptualization, visualization; T. Mutschler: conceptualization, writing – review and editing; P. Holderied: writing – review and editing; M.O. Weber: supervision, writing – review and editing; C. Breckenfelder: supervision, writing – review and editing; T. Freitag: investigation, methodology, writing – review and editing; D. Güther: investigation, methodology; M. Hummel: resources; M. Zeitler: resources, conceptualization; O. van Neerven: supervision, project administration. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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