ANALYSIS OF HEAT TRANSFER IN INFLATABLE SLEEPING PADS

ŞİŞİRİLEBİLİR UYKU PEDLERİNİN ISI TRANSFER ANALİZİ

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ABSTRACT

Sleeping bags and sleeping pads present inevitable equipment of all sportsman dedicated to mountaineering. Major part of thermal insulation of a person sleeping in a sleeping bag ensures the proper bag, but more than 40% of heat escapes through the sleeping pad (mattress) down to the ground or floor. However, despite the importance of sleeping pads, related research reports are almost missing. In the study, heat transfer mechanisms in hollow sleeping pads filled with the pressure air (to increase their thickness) and modern sleeping pads additionally filled with porous polyurethane foam is theoretically and experimentally analysed. From the theoretical analysis follows, that sleeping pads filled with porous polyurethane structures exhibit approximately 2 times higher thermal resistance then empty inflated pads, due to the reduction of free convection in the internal space of the pads. These theoretical findings were confirmed by the experimental results presented in the paper.

Keywords: Heat transfer, inflatable sleeping pads, thermal resistance, thermal absorbtivity, polyurethane filling.

ÖZET

Uyku tulumları ve uyku pedleri (şilteler), dağcılık sporunun vazgeçilmez ekipmanlarıdır. Uygun uyku tulumunun seçilmesi için en önemli özellik kişinin uyurken gerekli ısıl yalıtımını sağlamasıdır; ancak şilteden zemine doğru %40 ve daha fazla ısı kaybı meydana gelmektedir. Şiltelerdeki bu önemli kayba rağmen bu konuyla ilgili bir çalışma bulunmamaktadır. Bu çalışmada, kalınlıklarının arttırılması için boşlukları basınçlı hava ile şişirilmiş şilteler ile gözenekli poliüretan (PUR) köpükle doldurulmuş şilteler teorik ve deneysel olarak analiz edilmiştir. Yapılan teorik analizden, gözenekli PUR köpük yapılarına sahip şiltelerin şişirilmiş şiltelere göre iç boşluklardaki serbest konveksiyonun azalması nedeniyle yaklaşık 2 kat daha fazla ısıl direnç sergileyeceği bulunmuştur. Teorik analizle bulunan bu sonuç makalede verilen deneysel çalışma ile doğrulanmıştır.

Anahtar Kelimeler: Isı transferi, şişirilebilir uyku pedleri (şilteler) , ısıl direnç, ısıl soğurganlık, poliüretan dolgu.

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1. INTRODUCTION

Outdoor sports became very popular in last decades and sleeping in the nature is important part of these activities. Sleeping bags are portable textile products that enable sleeping and protecting people in wilderness under cool or cold outdoor climates. A sleeping bag presents an insulated covering for a person, essentially a lightweight quilt that can be closed with a zipper or similar means to form a tube, in which the sleeping person is almost completely wrapped and separated from the environment - see the example on the Figure 1.

The most advanced sleeping bags consisting of special fibres of feather deposited between two textile fabrics can protect their users up to -40°C outdoor temperatures.

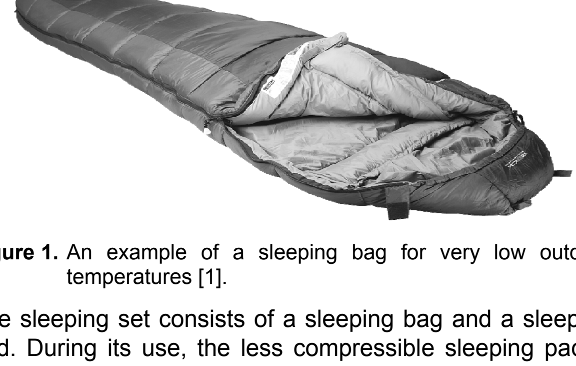

Figure 1. An example of a sleeping bag for very low outdoor temperatures [1].

The sleeping set consists of a sleeping bag and a sleeping pad. During its use, the less compressible sleeping pad is placed under the sleeping bag, as the sleeping bag is very compressed by its user during sleeping, and thermal resistance of the bag under the sleeping person would be very low. Thus, major part of thermal insulation of a person sleeping in a sleeping bag ensures this upper, free bag, but approx. 40% of heat escapes through the sleeping pad (mattress) down to the ground or floor [2]. Currently, many papers focused on improving thermal resistance of the fibre layers in sleeping bags were presented in scientific journals [2-4], but research papers on thermal insulation (resistance) *R* of sleeping pads are almost missing.

The aim of this study is theoretical and experimental analysis of heat transfer in traditional hollow sleeping pads filled with the pressure air (to increase the pad thickness) and also the analysis heat transfer in modern sleeping pads additionally filled with porous polyurethane foam. The achieved results should serve for design of sleeping pads with higher thermal resistance. Besides that, also lower weight, warmer thermal-contact feeling and certain compressibility of pads are welcome.

This basic utility parameter of sleeping pads, specific thermal resistance R [m^2KW^{-1}] is proportional to the pad thickness h [m] and inversely proportional to the effective thermal conductivity λ [$Wm^{-1}K^{-1}$] of the pad, as given by the definition of this parameter [5]:

$$R = h / \lambda \qquad (1)$$

Thus, in order to ensure the highest thermal resistance, the best pad should be thick enough and should exhibit the lowest effective thermal conductivity λ_{eff}. Contrary to the pads based on porous polymers (foams), the empty inflatable pads may offer sufficient thickness, but the λ level can be quite high. To reduce the thermal conductivity level, special filling inside the sleeping pad cavities must be used, in order to slow down the free convection inside the free space of the pad. In this study, heat transfer mechanisms in inflated sleeping pads filled with porous polyurethane foam (PUR) are theoretically and experimentally analysed. Experimental research involves testing of 14 samples of pads, which consist of porous polyethylene & vinylacetate pads and inflated pads. Also aluminium covered foam beach pad was tested, as it can serve as a sleeping pad. Various pads are shown in the Figure 2.

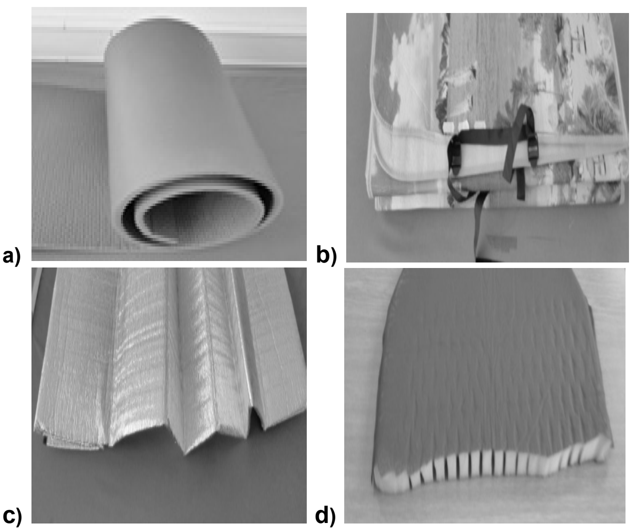

Figure 2. Examples of the studied pads a) cross-linked polyethylene foam pad b) Aluminium covered beach pad of polyethylene foam c) sleeping pad made of polyethylene foam covered by the aluminium foil d) inflatable pad with polyurethane perforated filling (section)

2. MATERIAL AND METHOD

2.1. THEORETICAL APPROACH

Historically, first sleeping pads which could be easily packed into a small tube consist of hermetically joined two rubber plates, which after inflation created the empty thermal insulating space. Heat in these inflatable pads is transferred mostly by radiation through the empty space inside these relatively cheap bags, where the radiation thermal conductivity λ_{rad} is given by the approximate relationship [6,7]:

$$\lambda_{rad} = 4\sigma\,[(T_1+T_2)/2]^3\,[(1/\varepsilon_1)+(1/\varepsilon_2)-1]^{-1} \text{ and } \lambda_{eff} = \lambda_{rad} + \lambda_{ekv}, \qquad (2)$$

Here T_1, T_2 are the temperatures of the layer surfaces and ε_1, ε_2 present the emissivity values of the internal walls of the pad (i.e. metal coating offers the lowest ε). However, big part of heat transferred in thick pads can be also transferred by free convection. The level of free convection depends on the magnitude of the so called Rayleigh dimensionless number (*Ra*):

$$Ra = Gr \cdot Pr = gL^3\beta\Delta t /(\nu a) \text{ and } Pr = \nu/a \qquad (3)$$

Here, g is the gravity acceleration, L is the gap thickness, β is the expansion coefficient, Δt is the temperature difference, ν is the kinematic viscosity, a is the thermal diffusivity. *Gr* and *Pr* are Grasshof number and Prandtl number, respectively which influence the coefficient ε_k, serving as the multiplication factor of thermal conductivity of air λ ($\lambda_{cond,air}$) [6] inside the pad with equivalent thermal conductivity λ_{ekv} . Some estimation for ε_k as described in literature [6] are also given in Table 1 where c and n are constants.

$$\lambda_{ekv}/\lambda = \varepsilon_k \; \varepsilon_k = c \cdot (Gr.Pr)^n \qquad (4)$$

Table 1. Practical values for ε_k calculations

Pr.Gr	C	n
< 10^3	1	0
10^3 -10^6	0,105	0,3
10^6 -10^{10}	0,4	0,2

To increase thermal insulation of pads, the researchers of the EMPA institute in Switzerland patented recently the use of the goose feather, whose microfiber based structure reduce the free convection effects and enable good compressibility of the pad. In our study, instead of feather, fine porous polyurethane compressible commercial structures were used, to reduce the effect of free convection. In order to decrease the mass of the pad and increase its compressibility, the structures (layers) are perforated as seen in Figure 3:

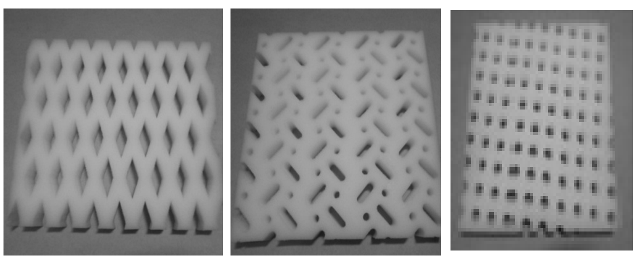

Figure 3. Perforated PUR layers (filling No. 1,2 and 3 – see in the Table 2)

2.2. EXPERIMENTAL ANALYSIS

In the study, thermal resistance, conductivity, absorptivity and thickness of 14 various commercial sleeping pads and layers were measured in the ALAMBETA instrument at the maximum contact pressure 1000 Pa, as this pressure more corresponds to the real conditions of the use of pads [8,9]. All these results are given in Table 2.

Thermal conductivity of full PUR layer was the lowest, about 0,055 W/m/K, between filled samples (No: 6-14), but the use of the perforation was inevitable, to ensure easy wrapping and lower mass of the pads. The average density of the studied PUR filling before the perforation was about 25 kg/m^3. Other details about the PUR filling were not available.

We also want to mention about **thermal absorptivity** *b* (Ws$^{1/2}$m^{-2}K^{-1}) presented in the Table 2 which expresses the relatively new parameter to characterize thermal contact feeling of fabrics as described in various papers [10 - 12] and defined as “warm – cool feeling” or the heat flow which passes between the human skin and the contacting textile fabric; the lower the value is the warmer the thermal contact feeling is. The following relation gives mentioned thermal property;

$$b = (\lambda \rho c)^{1/2} \quad (5)$$

where λ is thermal conductivity, and ρc is thermal capacity in J/m^3.

3. RESULTS AND DISCUSSION

In order to compare the experimental thermal comfort parameters with the theoretical ones in the [4], the radiation thermal conductivity λ_{rad}, the Rayleigh dimensionless number *Ra*, and the multiplication factor ε_k, serving for determination of the equivalent thermal conductivity of air λ_{ekv} in the free space inside the pads were determined. The value of the multiplication factor ε_k was found as 2,432. Thus, the λ_{rad} and λ_{ekv} were

$$\lambda_{rad} = 0{,}02478/0.3958 = 0{,}0625\ [Wm^{-1}K^{-1}] \quad (6)$$

$$\lambda_{ekv} = \lambda_{Air.}\ \varepsilon_k = 0{,}026\ .\ 2{,}432 = 0{,}0632\ [Wm^{-1}K^{-1}] \quad (7)$$

The last objective of the calculation is the determination of the effective λ_{eff} (total), in which the PUR filling (mentioned as filling No.1 in Table 2) coefficient μ plays important role (its levels are presented in the Table 3.

$$\lambda_{eff} = (\mu\ .\ \lambda_{PUR}) + (1-\mu)\ (\lambda_{ekv} + \lambda_{rad}) \quad (8)$$

After inserting the previous calculated value we get

$$\lambda_{eff} = (0{,}8\ .0{,}0550) + (0{,}2)\ (0{,}0632 + 0{,}0625) = 0{,}0692\ [Wm^{-1}K^{-1}] \quad (9)$$

The theoretical and experimental results for inflated pads and other layers are now compared in the Table 3. The correlation between measured and theoretical thermal conductivity and resistance values of inflated samples was 0.996 and 0.986, respectively.

Table 2.. Thermal properties of sleeping pads and layers measured at the pressure 1000 Pa (cv expresses the level of variation coefficient in %)

Sample No.	Sample type	Thermal conductivity [Wm^{-1}K^{-1}]		Thermal absorptivity [Ws$^{1/2}$m^{-2}K^{-1}]		Thermal resistance [m^{2}KW^{-1}]		Thickness [mm]	
		λ	cv	b	cv	R	cv	h	cv
1	Aluminum pad	0,0349	2,25	55,57	4,03	0,0768	5,83	2,68	7,41
2	Beach pad	0,0385	1,85	71,28	3,55	0,0556	2,50	2,15	3,89
3	Karimate 1	0,0443	1,02	50,577	7,82	0,2589	1,18	11,43	0,88
4	Matrasse 1	0,0403	0,75	47,18	2,27	0,2413	1,16	9,72	1,02
5	Q-pad	0,0413	1,57	53,79	4,01	0,2453	1,4	10,10	1,53
6	Camping pad green	0,0639	4,06	71,35	9,65	0,3205	4,18	20,44	2,04
7	Outdoor pad blue	0,0696	6,36	60,46	5,62	0,3311	6,01	22,96	0,62
8	RE-pad	0,0632	4,75	55,76	10,8	0,3755	4,84	23,66	1,34
9	Partly inflatable pad	0,0694	10,65	50,47	16,22	0,395	11,99	27,07	1,00
10	Filling No. 1	0,0674	4,37	31,08	18,11	0,3684	4,23	24,76	0,37
11	Filling No. 2	0,0714	6,97	31,40	25,43	0,3312	7,01	23,53	0,37
12	Filling No. 3	0,0629	3,48	32,72	16,18	0,3695	3,42	23,19	0,43
13	PUR foam full	0,0550	4,39	22,51	16,92	0,4977	4,71	27,33	0,28
14	Air cylinder 23 mm	0,1387	0,72	13,37	18,71	0,1457	1,07	20,21	0,53

Table 3. Comparison of theoretical and experimental results of thermal parameters of inflated pads and of Air cylinder + PUR foam full for comparison

Sample No.	Sample type	Thermal conductivity		Thermal resistance		Thickness	Thermal resistance of the samples related to the resistance of full PUR
		λ [Wm^{-1}K^{-1}].		R [m^2.KW^{-1}]		h [mm]	**%**
		measured	theoretical	measured	theoretical	measured	calculated
6	Camping pad green	0,0639	0,0672	0,3205	0,3043	20,44	80
7	Outdoor pad blue	0,0696	0,0683	0,3311	0,3360	22,96	80
8	RE pad	0,0632	0,0687	0,3755	0,3446	23,66	80
9	Partly inflatable pad	0,0694	0,0702	0,3950	0,3855	27,07	75
10	Filling No. 1	0,0674	0,0692	0,3684	0,3580	24,76	80
11	Filling No. 2	0,0714	0,0720	0,3312	0,3268	23,53	75
12	Filling No. 3	0,0629	0,0678	0,3695	0,3423	23,19	79
13	Air cylinder 23 mm	0,1387	0,1152	0,1457	0,1754	20,21	29
14	PUR foam full	0,0550	-	0,4977	-	27,33	100

As mentioned in the Eq. 8 the free convection coefficient *K* reached the value 2,42. That is why the “convection” thermal conductivity λ_{ekv} of the open air layer was about 0,0632 [$Wm^{-1}K^{-1}$]. The calculated radiation thermal conductivity λ_{rad} for free space was found about 0,0625 [$Wm^{-1}K^{-1}$]. Thus, effective λ_{eff} of pads without filling (when rubber frame is not considered) is given by the pure sum of λ_{ekv} and λ_{rad} , which yields 0,125 W/m/K or a bit less, when reflective walls were used. Thus, when the perforated structures with 80% filling were employed, then the effective λ_{eff} of the inflated pads with PU filling was 0,0692 [$Wm^{-1}K^{-1}$] only, which presents only 55% of thermal conductivity of pads without filling.

4. CONCLUSIONS

It is found that thermal resistance R levels of modern inflated sleeping pads containing filling against free convection are more than two times higher than thermal resistance levels of previous sleeping pads without any filling. Here, the inflation principle enables to keep the thickness of pad relatively high (contrary to the old simple foam pads), and the anti-convection fillings reduce the negative effect of free convection on the final thermal resistance levels. As shown in the Table 3, the theoretical and experimental results are in very good agreement.

In the next step of this research, the effect of the emissivity levels of internal walls of the inflated pads on the resulting thermal resistance will be also analysed. However, due to the presence of relative compact filling, which attenuate the radiation heat flow, big effects are not expected.

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