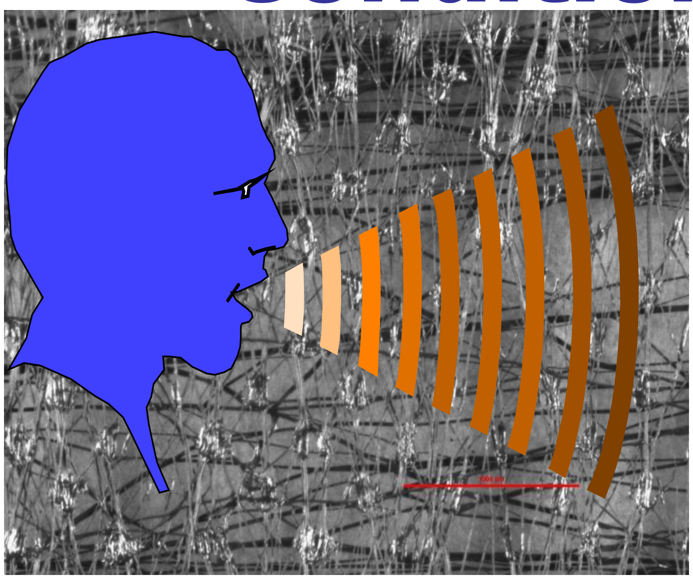
World Textile Conference-2 by TAI , Mumbai Sptember 2016

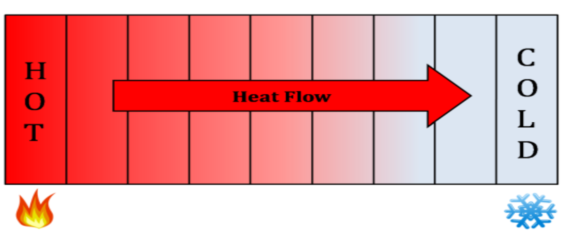
Thermal Insulation Layers for Extreme Cold Weather Conditions



Jiri MILITKY, Rajesh Mishra, Dana KREMENAKOVA

Technical University of Liberec

Textile Faculty,
Dept. of material engineering
Czech Republic



Engineers (Scientists) are from Mars, Fashion Designers (Industry People) are from Venus

Overture

Smart clothing have till yet serious limitations for practical use because they are: too expensive to produce, uncomfortable to wear, without aesthetic sophistication, and are not marketed in a lifestyle way.

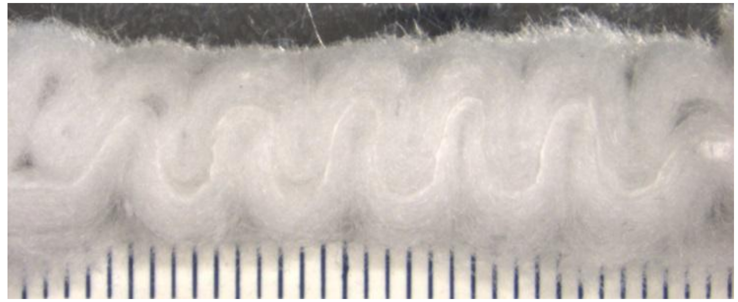
• There are biased information oriented to highlight of „smartness“ or scientific content and to suppress weakness in real use.

• Instead of seriousness there are appeared „newspaper stories“ oriented to dazzle of customers (organic cotton, bamboo fibers etc.)

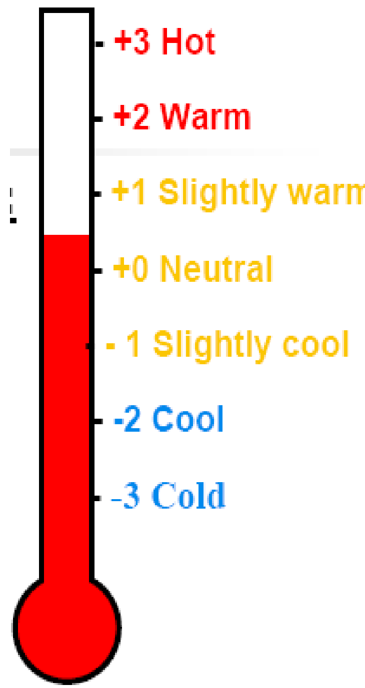
• From education in the universities to targeting consumers in stores, the approaches diverge and rarely cross paths. This has affected the (fashion) industry’s limited awareness of innovative new materials and has caused scientists to develop soft technology that does not cater to the needs of the (fashion) market.

A. Chang: Wearable Futures Conference Hybrid Culture in the Design and Development of Soft Technology, September 14 – 16, 2005

Agenda

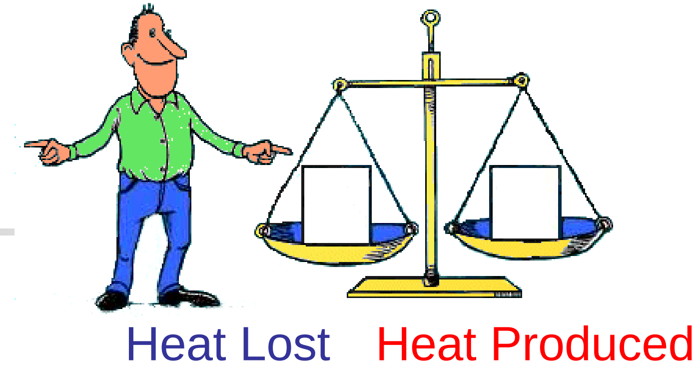


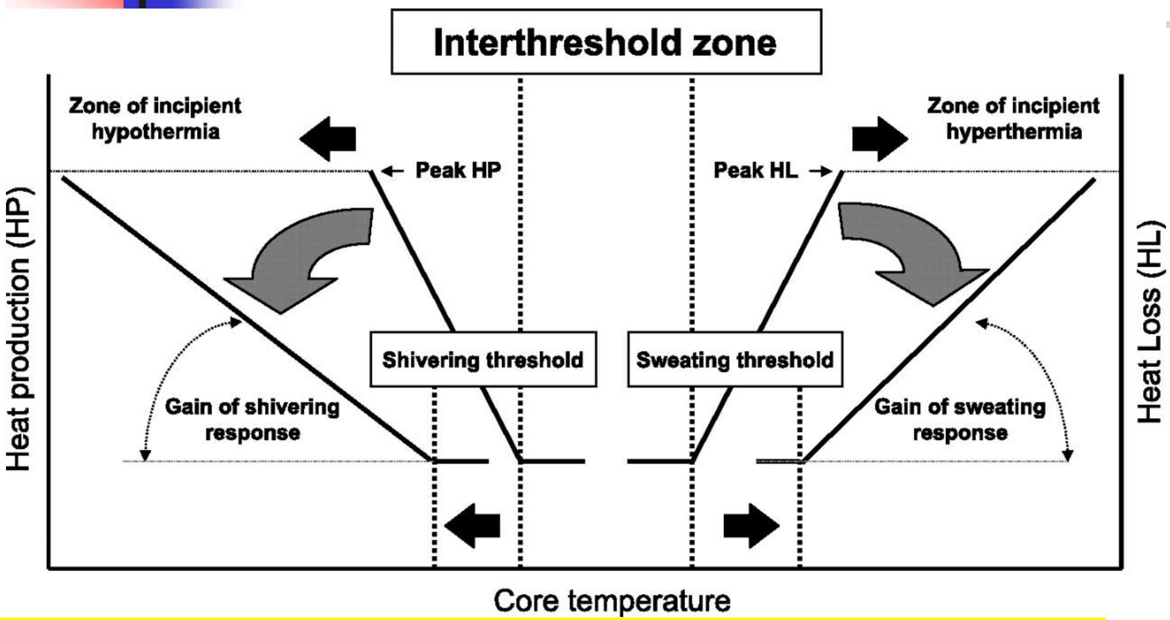
- Thermal comfort and fabric construction
- Fabrics characteristics
- Selection of fibers
- Selection of construction nonwovens
- Nanolayers in sandwich structures
- Types of layering



Thermo-physiological Comfort

Heat produced by metabolism equals the heat lost from body.





2 nd World war = in winter 25% Germans died due to legs frostbite

The clothing of cold weather is normally bulky and used in more than one layer, providing thermal insulation and protection against wind penetration.

The cold weather clothing is designed to protect the body or areas that are exposed to risky climatic conditions.
Methods to avoid unnecessary heat loss and discomfort include, putting on clothing, increasing physical activity, finding some protection, exposing to sunlight, etc.

Properties Required for Cold Weather Clothing

LAYER	BASIC REQUIREMENT	DESIGN CONSIDERATIONS
Outer Shell	• Durable • Waterproof • Windproof • Breathable	• Equipment Stowage • Wind and water proof with venting to reduce thermal burden during exertion • Ease of donning / doffing
Mid Layer	• Lightweight • Insulating • Breathable	• Modular / Scaleable approach to vary insulating characteristics based on conditions and operational requirements
Base Layer / Underwear	• Breathable • Insulating • Wicking – moisture management • Comfortable against the skin	• Sanitary layer requiring frequent washing • Modular approach to vary insulating characteristics based on conditions

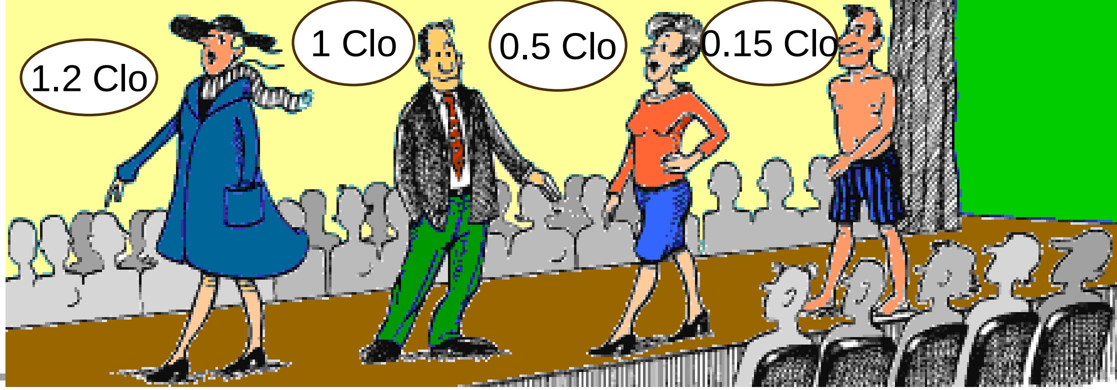
Clothing Design Requirements

• **Base Layer:** It is the inner most layer performing the wicking action. Being highly permeable, it pulls the moisture away from skin and passes on to the next layer.

• **Middle Layer:** It is the insulation layer, which traps the warmth created by body heat, and at the same time allows perspiration to keep moving. The insulation layer is generally a combination of multiple layers rather than one.

• **Outer Layer:** The outer shell layer is to provide protection from wind and rain, and also needs to be breathable

Thermal comfort units



One ***clo*** corresponds to intrinsic insulation of business suit worn by sedentary resting male in a normally ventilated room at 21ºC and 50 % RH and air ventilation of 0.1 m/s. In these conditions are man feelings as quite comfortable.

Total metabolic heat – 1 MET=58 Wm^{-2}

24% evaporation lost by comfort. t. - skin 33°C

76% - through clothing by K+C+R ~ 44Wm^{-2}

Total thermal resistance of clothing ~ (33-21)/44=0,2715 m^2KW^{-1}

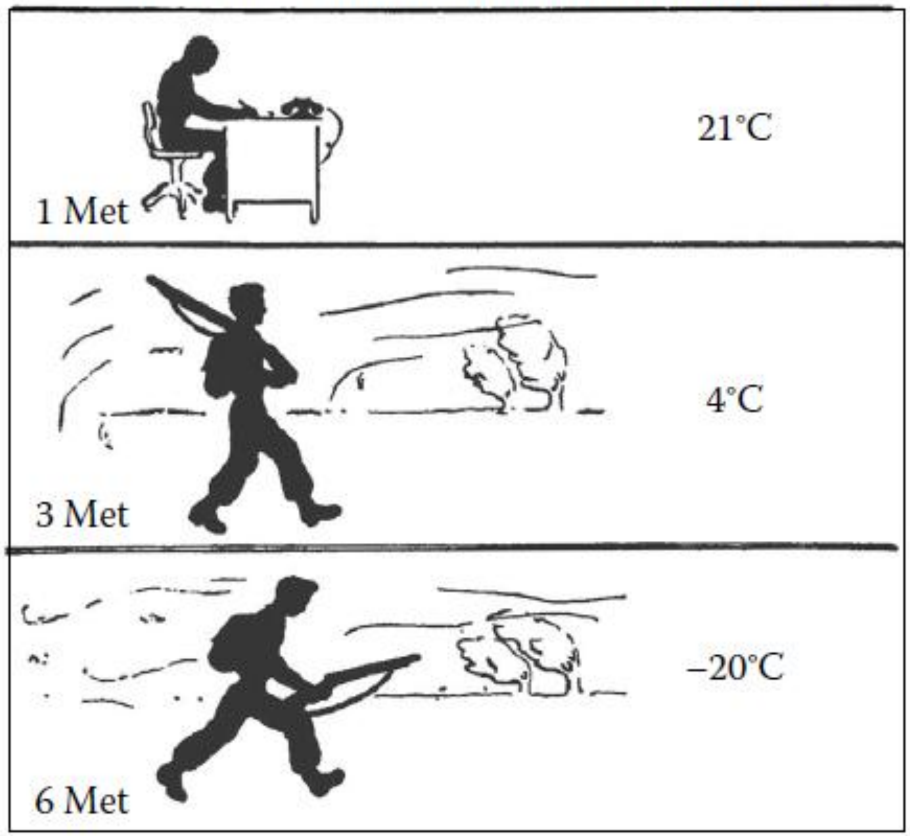
Resistance of surrounding air layer 0,12 m^2KW^{-1}, air cond. 0,024$Wm^{-1}K^{-1}$ ⇒ thickness 0,12x0,024=0,0028m *Clo = thickness/(0,155 therm. cond.)*

Isolation of clothing system only ~ 0,2715-0,12=0,155 m^2KW^{-1} ~ 1 *clo*

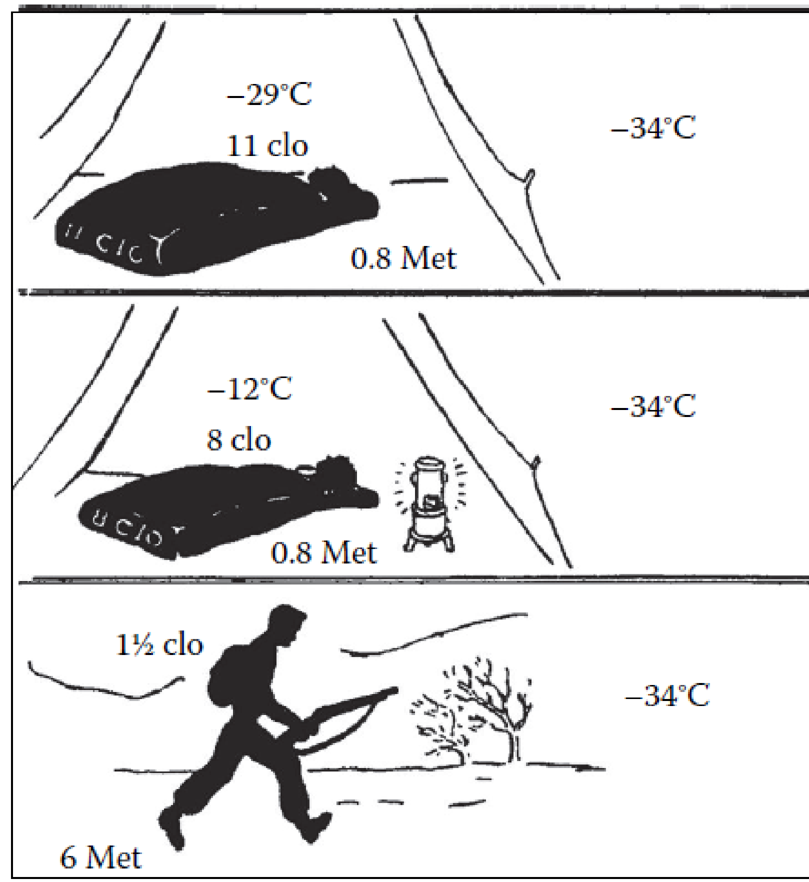
CLO and cold conditions

Activity	Energy cost (watts)
Sleeping	70
Resting	90
Walking 1.6km/h (1mph)	140–175
Walking 4.8km/h (3mph)	280–350
Cycling 16km/h (10mph)	420–490
Hard physical work	445–545
Running 8km/h (5mph)	700–770
Sprinting	1400–1500

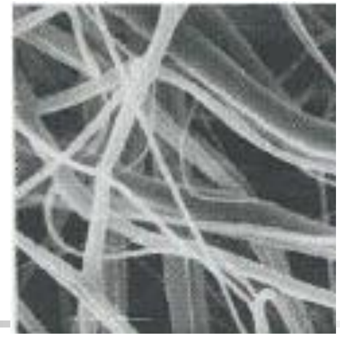
What 1 clo of clothing insulation is good for

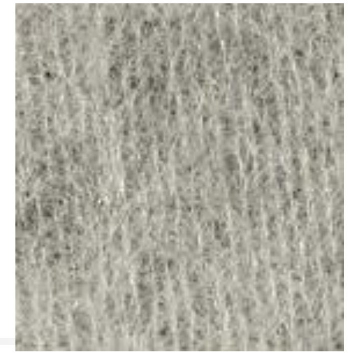


How many clo units are needed?



Textile Layer Characteristics





Characteristics of fabric structural parameters connected with transport comfort properties

W is areal mass [g/m^2 = gsm],
H is fabric thickness [mm],
v_{fabric} is volume portion of fibers [-],
ρ_F is fiber density [kg/m^3],
ρ_{fabric} is fabric density [kg/m^3],
P is fabric porosity [-]

Fabric density

$$\rho_{fabric} = \frac{W}{H}$$

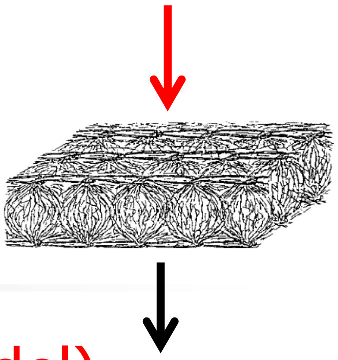
$$v_{fabric} = \frac{W}{H\,\rho_F} = \frac{\rho_{fabric}}{\rho_F}$$

Total fabric porosity

$$P = \frac{volume\ of\ air\ spaces}{total\ fabric\ volume} = 1 - \frac{\rho_{fabric}}{\rho_F}$$

Woven
Knitted
Nonwoven

Thermal insulation of fabric



The thermal conductivity of fabric (serial/paralel model)

$$\lambda_T = 0.5\left((1-P_F)\lambda_a + P_F\ \lambda_f + \frac{\lambda_a\ \lambda_f}{(1-P_F)\ \lambda_f + P_F\ \lambda_a} \right)$$

λ_a: 0.024 $Wm^{-1}K^{-1}$

$$RT = \frac{\Delta T}{Q} = \frac{h}{\lambda}$$

Thermal conductivity of textile fibres is generally dependent on their chemical composition, morfology, porosity, structure and content of water.

For practically nonporous amorphous polypropylene fibre is λ = 0.172 [W $m^{-1}K^{-1}$] and for porous acrylic fibre or PET (40 % crystallinity) is λ = 0.288 [W $m^{-1}K^{-1}$].

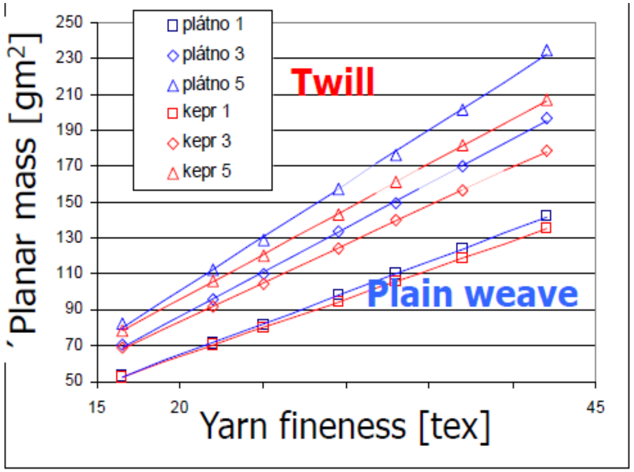
For less regular crystalline polymers is thermal conductivity dependent on the ratio of densities ρ_c/ρ_a of 100% crystalline and fully amorphous polymers

Thermal resistance of fabric

$$I_c = \frac{H}{0.155\ \lambda_T}\ [clo]$$

I_c (under wear) is less than 45 10^{-3} m^2K/W

Fabric planar mass



Porosity of fabrics P [-] is given by relation

$$P = 1 - \frac{W}{H\rho_F}$$

where the planar mass = W [kg m^{-2}] (usually [g m^{-2}] i. e. [gsm]), thickness = H [m] (usually [cm]) and fiber density = ρ_F [kg/m^3].

The W is equal to

$$W = (1 - P)H\rho_F$$

It is visible that the planar mass *W* is directly proportional to the fabric thickness.

Required fabric planar mass

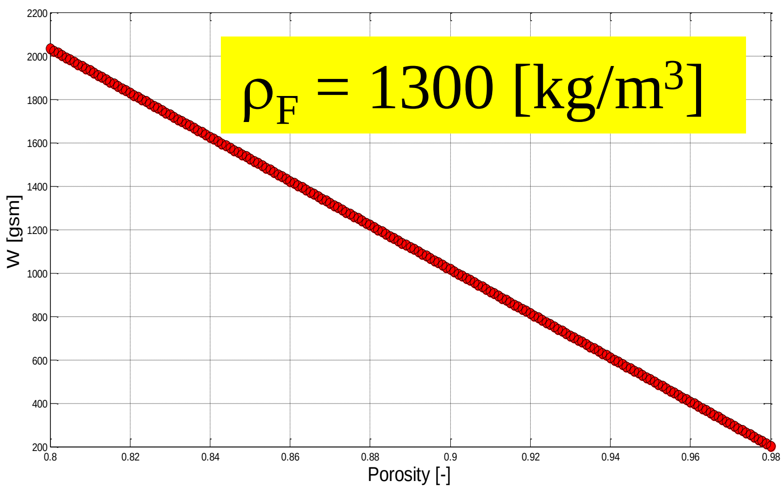
It is practically impossible to construct the effective insulating layer for outside temperature – 25°C with planar mass below 200 g m^{-2}.

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

$$W = (1 - P)0.155\,\lambda\,I_c\,\rho_F$$

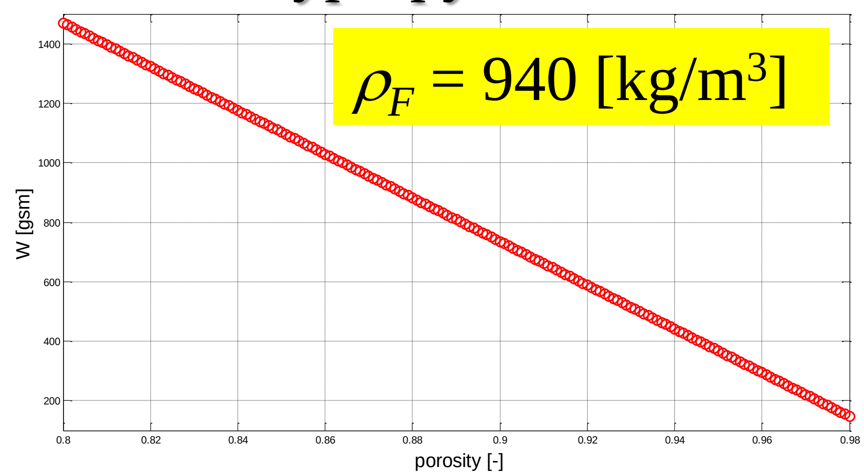
For T_a = -25°C is I_c = 1.6813

thermal conductivity 0.030 [W m^{-1}K^{-1}]



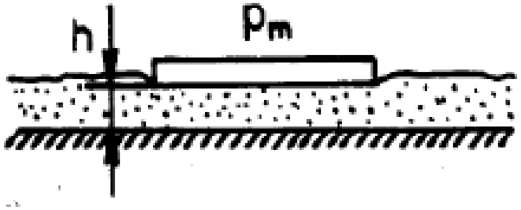
For very high porosity 0.9800 (i.e. the only 2% of fabric is fibrous phase) is still planar mass 203.2650 g m^{-2}.

Polypropylene

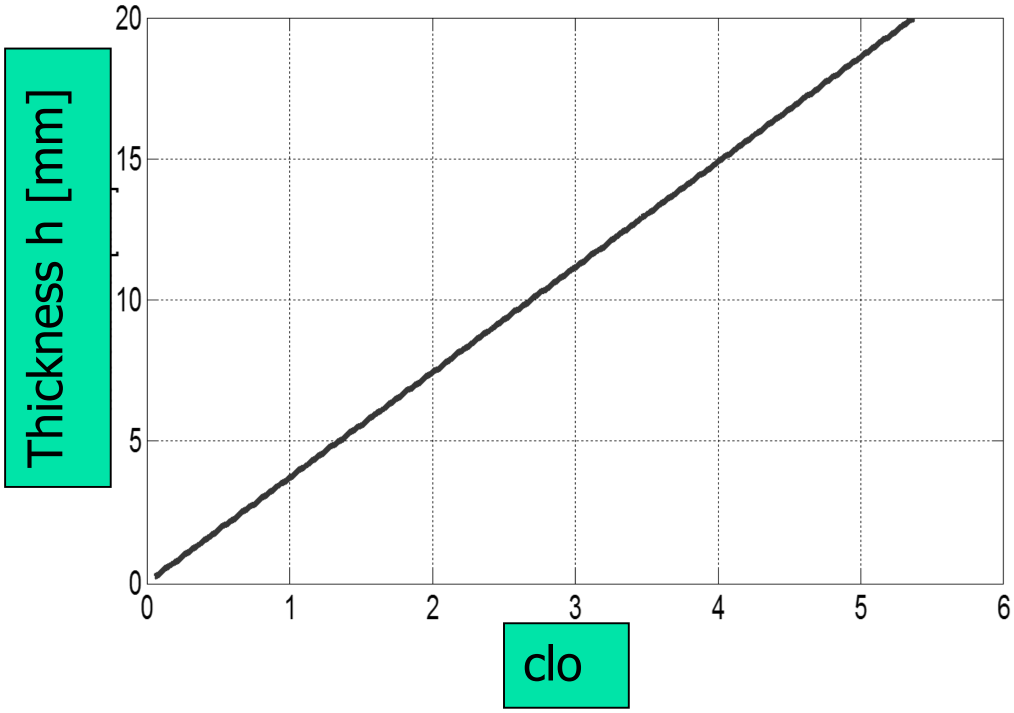


Planar mass is lower but still for very high porosity P = 0.9700 is required planar mass W = 220.46 g m^{-2}

Minimum fabric thickness



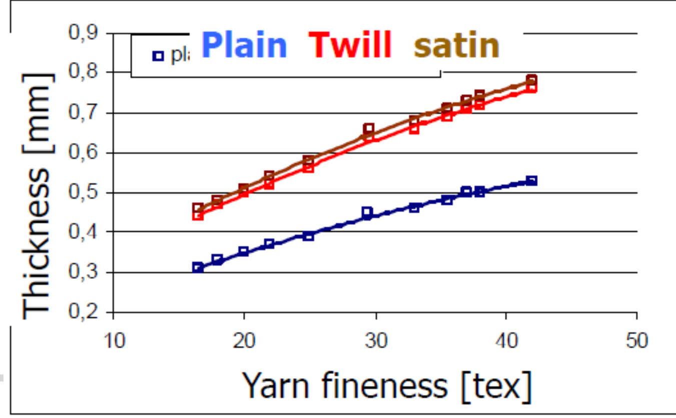
The minimum thickness of textile layer with highest thermal insulation (with the same thermal conductivity as air) ensuring chosen *clo*



It is clear, that for required *clo* = 4, is minimal thickness of textile layer equal to 15 mm

For effective thermal insulation especially at low temperatures it should be selected **sufficiently high thickness** of textile layer.

Required fabric thickness



Required thermal resistance *Ic* [clo] depends on ambient temperature Ta and human activity expressed as Met. For no extra human activity is valid

$$I_c = 1.372 - 0.01866 T_a - 0.0004849 T_a^2 - 0.000009333 T_a^3$$

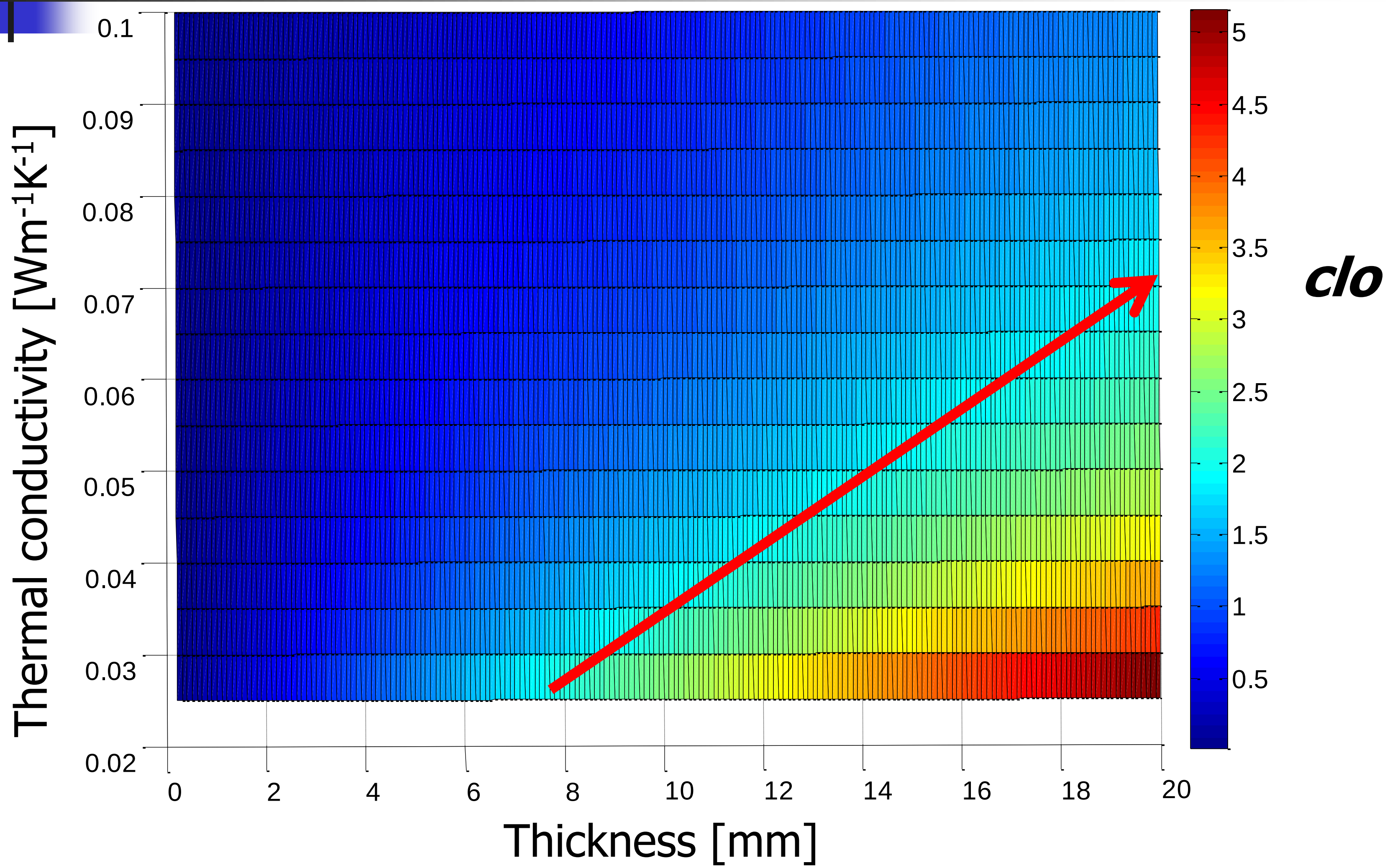
The thermal resistance is related to fabric thickness

$$I_c = \frac{H}{0.155\,\lambda}\ [clo]$$

where λ [W m^{-1}K^{-1}] is thermal conductivity. For given thermal conductivity λ [W m^{-1}K^{-1}] and I_c [clo] is required thickness H [m] equal to

$$H = 0.155\,\lambda\, I_c$$

Dependence of clo on the thermal conductivity and thickness of fabrics



Comfort air temperature

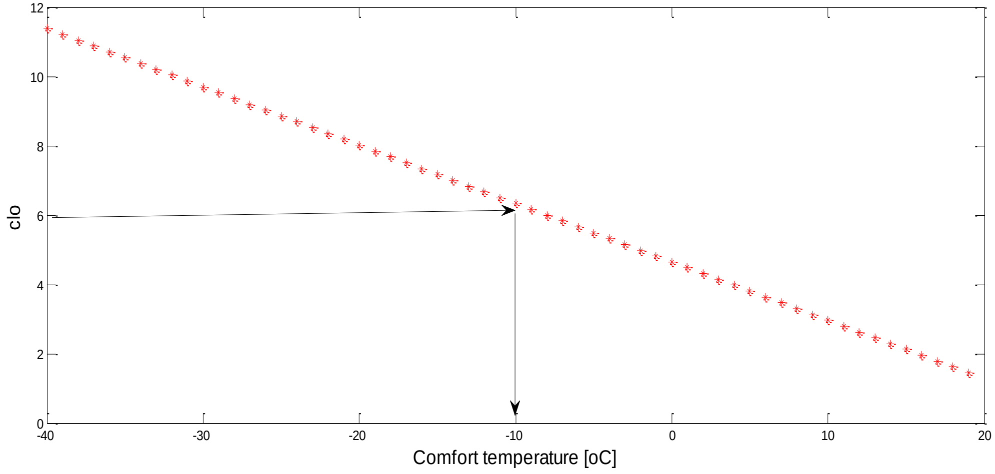
At **comfort air temperature** T_{ac} are thermal loss of dressed human in balance with metabolic rate.

$$T_{ac} = 27.6 - 5.94\ R_O$$

where R_O [clo] is cloth thermal insulation. For cloth 1Clo is comfort air temperature equivalent to 21.7 °C.

$$R_o = \frac{(27.6 - T_{ac})}{5.94}$$

For the comfort temperature T_{ac} = -10°C it should be $R_o = I_c$ = 6.33 clo and for the comfort temperature T_{ac} = -20°C it should be $R_o = I_c$ = 8 clo



General procedure for optimization of insulation layer I

There exist a lot of approaches how to calculate *clo* of clothing for assuring comfort for selected climatic conditions (temperature, wind speed, altitude) and human activities. Simple is calculation of h_{opt}

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

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

is expressed by equation

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

For temperature -20^{o}C is $h_{opt} = 0.9312\ \lambda$.

For design purposes there are three main steps how to optimize textile layer composition and thickness.

General procedure for optimization of insulation layer II

1. Selection of suitable fiber type

Usually the fine round fibers from polyester or polypropylene are recommended. From point of view of porosity the finer crimped fibers with complex cross section profile are the best ones. But generally speaking key role 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 relative high thermal conductivity.

Decrease of fiber diameter from 10 to 3 microns leads to 26 % increase of thermal insulation (Fan)

General procedure for optimization of insulation layer III

2. Fabric construction

Construction of plane structure with sufficient porosity P_o air permeability A_p and planar mass W in *gsm.* Wowen and knitted structures are generally worse in comparison with nonwovens because the 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.

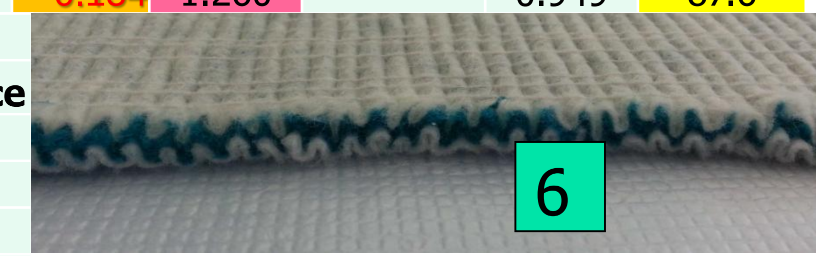
Polartec Fibertech

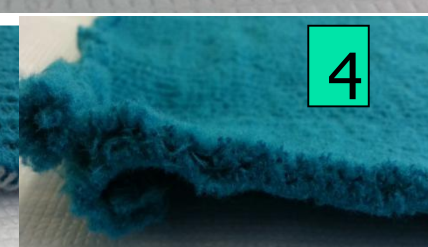
Improvement of Nonwovens Thermal Insulation

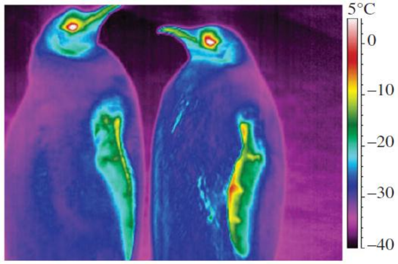
ROTIS

			CLO	H	AP	P	W
				mm	$lm^{-2}s^{-1}$	-	gm^{-2}
A1	1	Polartec Alpha PES multifil,	0.246	2.165	1865	0,966	100
A2	2	Polartec Alpha 1 layer compactness 1,6	0.497	4.325	1200	0,969	178.9
A3	3	Polartec Alpha 1 layer compactness 2	0.626	5.070	643,5	0,955	304.1
A4	4	Polartec Alpha 2 layers compactness 1,6	**0.892**	4.515	354,5	0,962	234.5
A5	5	Polartec Alpha 1 layer compactness 1,6 Fibretex 1 layer compactness 1,6	0.809	7.265	277	0,946	531.7
A6	6	Fibretex 1-3 layer compactness 1,6 Polartec Alpha 2 layer compactness 1,6	0.763	7.595	194,5	0,931	710.1
A7	7	Fibretex	0.154	1.260	1430	0.949	87.6

	Alambeta	
sample	**Thermal conductivity**	**Thermal resistance**
	$Wm^{-1}K^{-1}$	m^2KW^{-1}
1	0.0351	0.0381
2	0.0420	0.0770
3	0.0457	0.0970
4	0.0478	0.1383
5	0.0487	0.1253
6	0.0533	0.1183
7	0.0338	0.0238



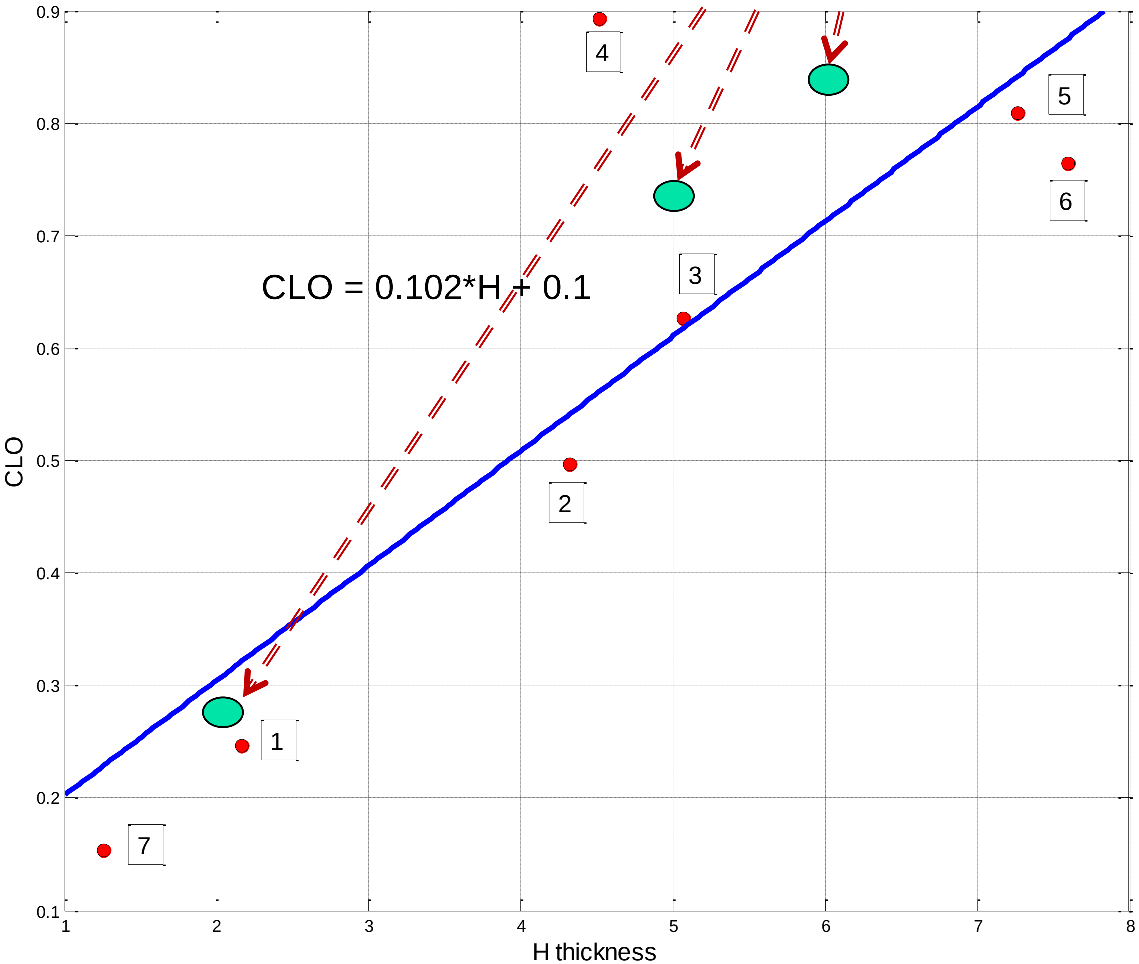


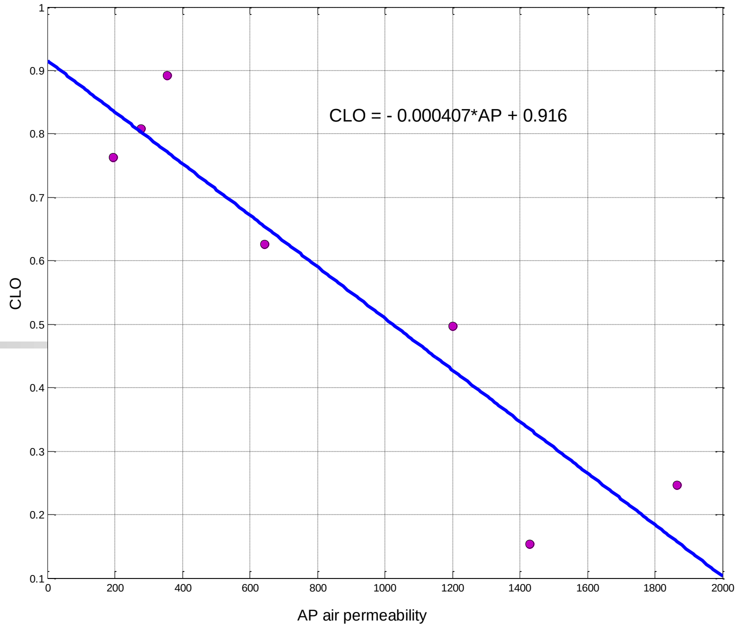


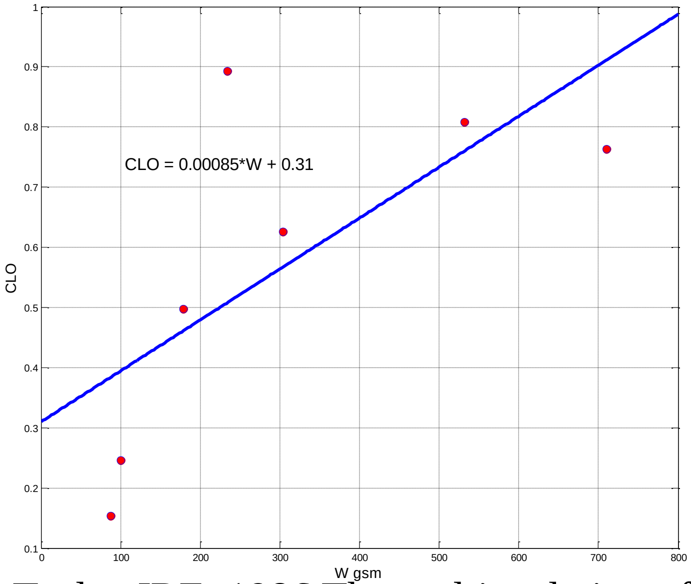
CLO trends

CLO = 3.9

H = 27







Taylor JRE. 1986 Thermal insulation of the down and feathers of Pygoscelid penguin chicks and the unique properties of penguin feathers. Auk 103, 160–168

General procedure for optimization of insulation layer IV

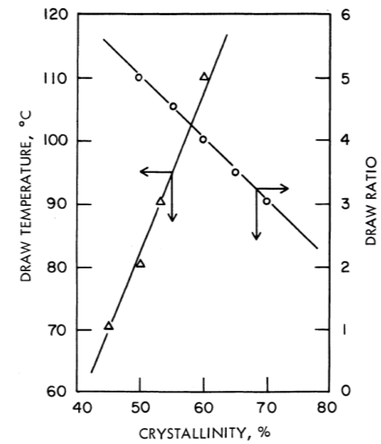
3. Required thickness

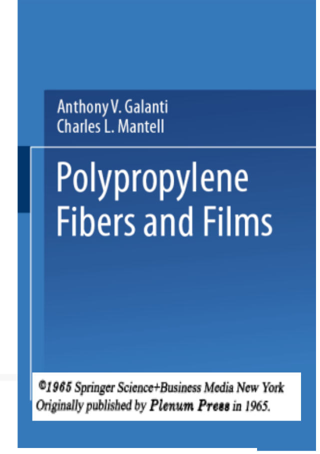
Thickness can be predicted from knowledge of external conditions (temperature, wind speed, altitude and human activities) and from thermal conductivity of textile layer λ_c. From predicted thickness h_{opt} and λ_c it is simple to calculate thermal insulation in *clo* and compare results with IREQ for 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

Selection of fiber - POP



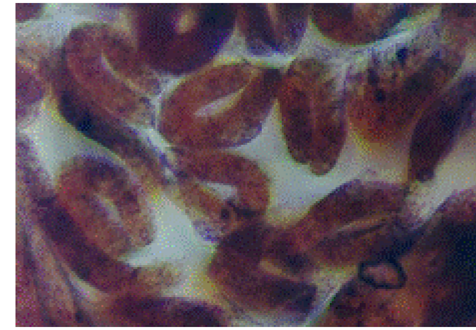


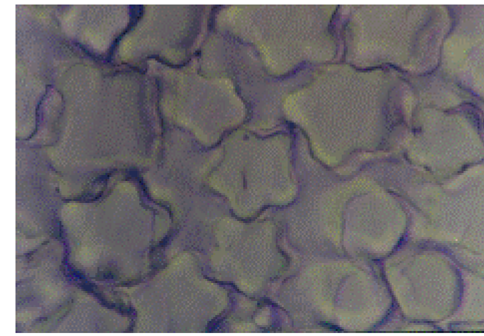
POP has lowest thermal conductivity of any natural or synthetic fiber (6.0 compared to 7.3 for wool, 11.2 for viscose and 17.5 for cotton). POP fibers retain more heat for a longer period of time, have excellent insulation properties in apparel, and combined with its hydrophobic nature keeps wearer dry and warm. Warmer than wool.

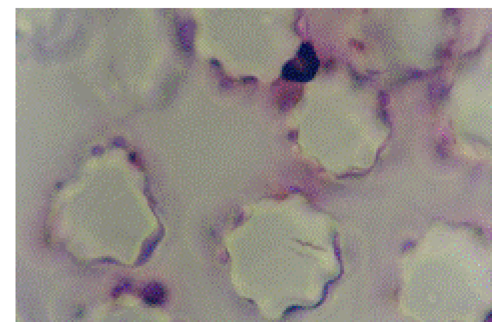
Material	Heat conductivity, relative to air
Air	1.0
Polypropylene	6.0
Wool	6.4
Acetate	8.6
Viscose	11.0
Cotton	17.0

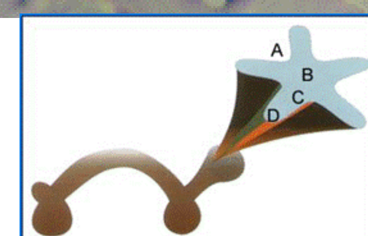
material	specific volume [cm³/g]
polypropylene	1,1
polyamide	0,88
wool	0,76
polyester	0,72
cotton	0,66

Cross section shape









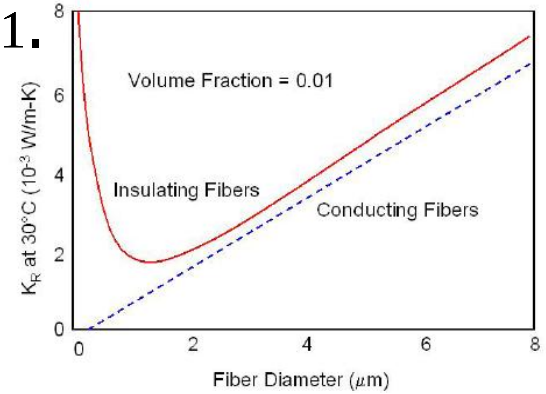
Knit Structures

Cross Section	Thermal Resistance		Thermal Conductivity	
	Dry state	Wet state	Dry state	Wet state
Star 5	22,4	10,4	61,2	130,0
Star 8	25,3	20,2	55,8	90,1
O (around)	24,7	10,6	59,7	146,0
U	27,1	8,9	52,1	133,6

The best thermo physiological comfort properties corresponds to the star cross section with 5 points.

J. Appl. Phys. **55** 4065-4071.

For polyester fibers is optimum diameter around 1 μm,



Fiber fineness I

Thermal radiation can be 40 to 50% of the total heat transfer in low-density fibrous insulation at moderate temperatures. Infrared radiation (heat) wavelengths are in the range of 0.7 to 100 μm. Fiber diameters less than 0.5 μm would be too small to interact with thermal radiation. However, it is known that fibers smaller than 1 to 3 μm can increase the thermal resistance of polymer fiber insulation materials.

FARNWORTH :Nonwovens composed of randomly oriented fibers of length *L*, radius r, and thermal emissivity *e*.

Coefficient of radiative conductivity [W/ (m K)]

$$h_r = 8\,\sigma\, T_o^3\, \frac{r}{e}$$

where

$$To = \frac{(Ts + Ta)}{2}$$

Absorption of radiation by randomly oriented fibers. Absorption constant β

$$\beta = \frac{v_f\ \varepsilon}{r}$$

σ=5.67x10^{-8} W m^{-2} K^{-4} is Stefan Boltzman constant

The radiative heat transfer q_r

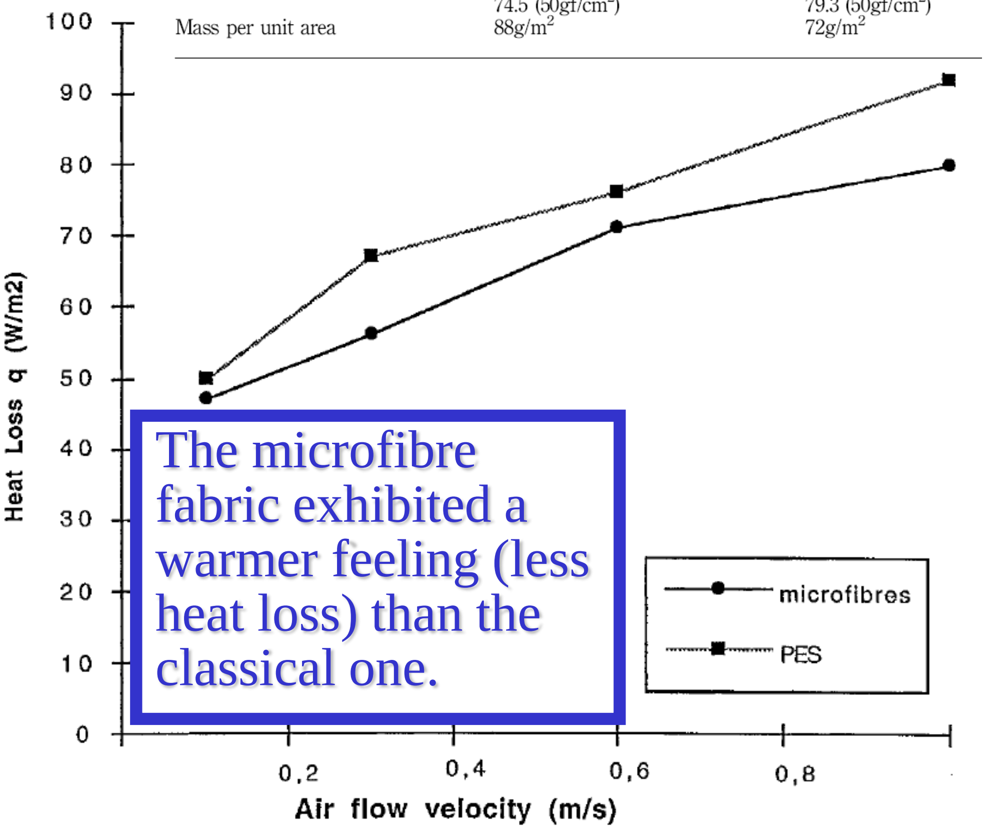
$$q_r = -h_r \frac{(Ta - Ts)}{H}$$

Conclusion: finer fibers (low radius) have smaller radiative heat transfer and higher radiation absorption

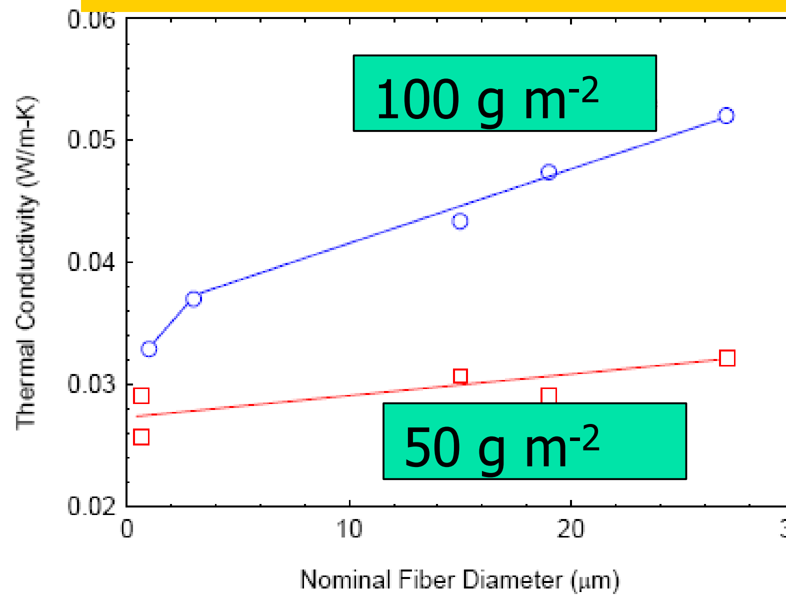
Fiber fineness II

Material	Microfibres polyester	Classical polyester
Warp	0.7dtex (filaments)	2.5dtex (filaments)
Weft	1dtex (fibres)	4dtex (filaments)
Pattern	Plain	Plain
Warp count	43 yarns/cm	29 yarns/cm
Weft count	36 yarns/cm	23 yarns/cm
Thickness	0.62mm (0.5gf/cm^2) 0.25mm (50gf/cm^2)	0.45mm (0.5gf/cm^2) 0.26mm (50gf/cm^2)
Compressibility (%)	61	43
Air content (%)	89.7 (0.5gf/cm^2) 74.5 (50gf/cm^2)	88.4 (0.5gf/cm^2) 79.3 (50gf/cm^2)
Mass per unit area	88g/m^2	72g/m^2

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.

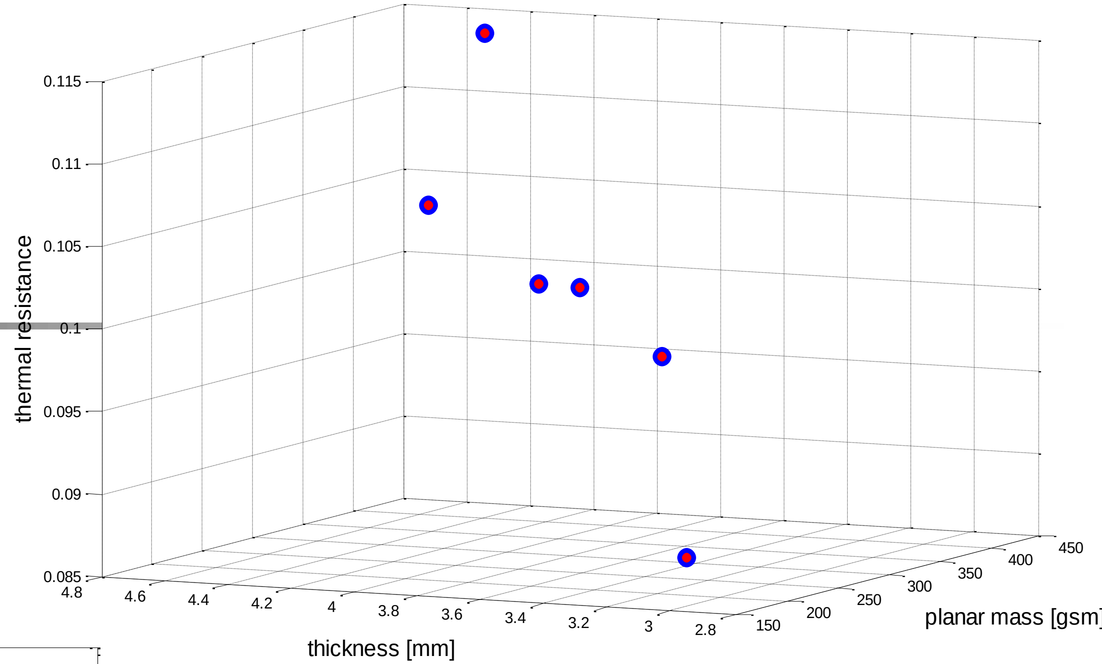


The microfibre fabric exhibited a warmer feeling (less heat loss) than the classical one.

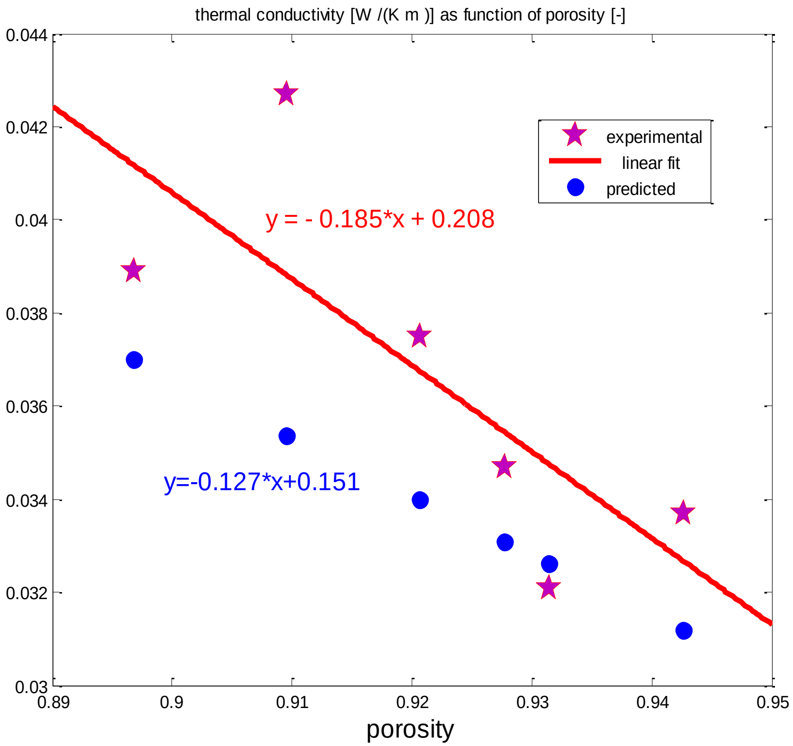


International Journal of Clothing Science and Technology, **12**, No. 2, (2000), pp. 84-95.

Nonwovens

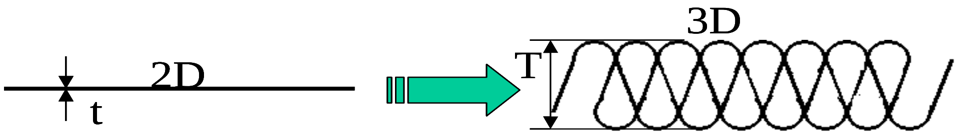


Needled punched polypropylene nonwoven fabrics



number of pre-needling strokes: 600 1/cm
depth of needle penetration (pre-needling): 7.5 mm,
number of needle strokes per area: 370 1/cm
depth of needle penetration: 4.0 mm

Thermal conductivity of POP 0.252 W/(m·K) was selected

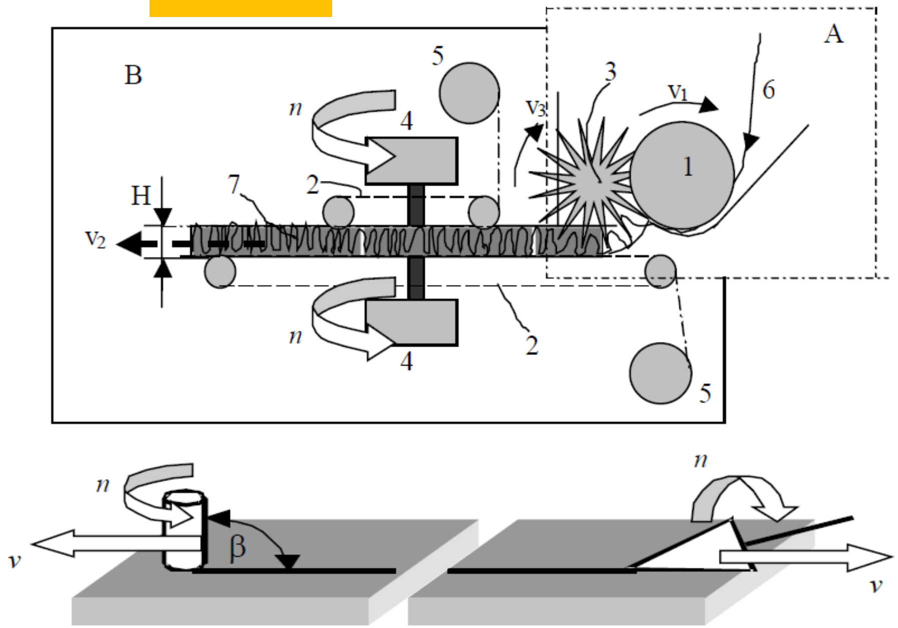


Selection of nonwovens type

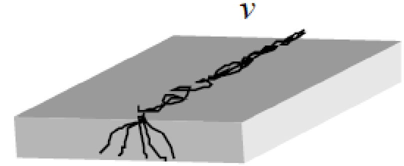
Construction of plane structure with sufficient porosity P_o air permeability A_p and planar mass W in *gsm*. Nonwoven structures can be tailor made by simple modification of fabrication process. Especially perpendicularly laid structures of **Rotis or Struto** type can be prepared in huge variation of porosities due to changing density of “waves”.

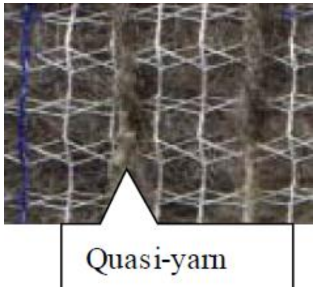
1…feed roller,
2…delivery roller,
3…working roller,
4…rotating spindles,
5…reinforcing textile material,
6…web,
7…product

Rotis



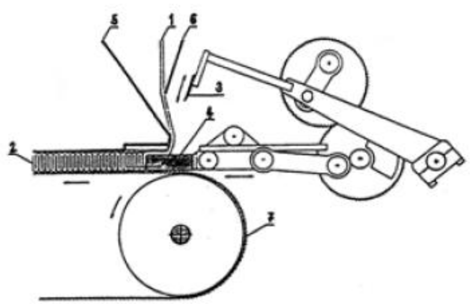
$$T = \frac{n}{v}$$



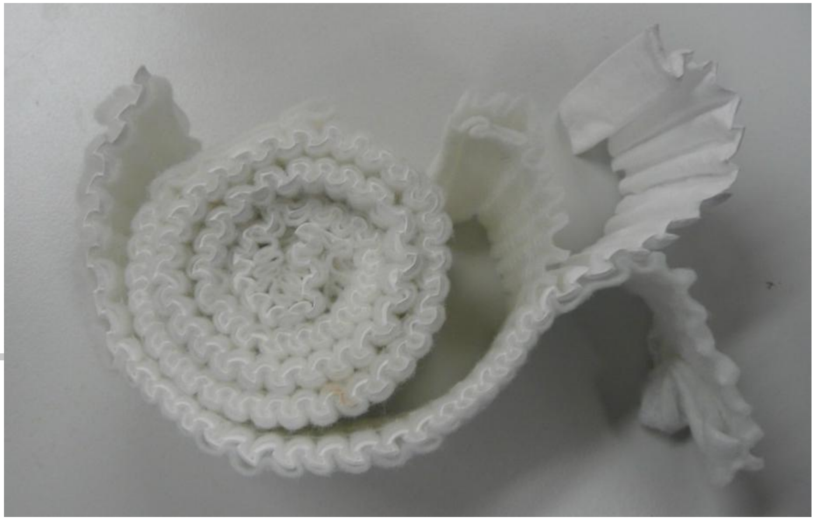


Struto

Stabilization by thermo bonding



ROTIS optimal adjustments



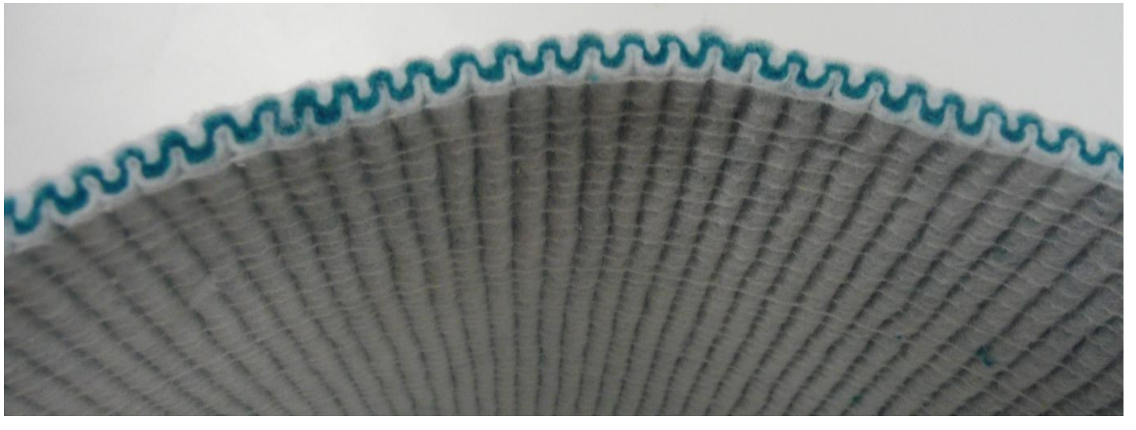
For standard product thickness T = 7 mm, mass G = 600 g/m^2, fold numbers ρ 300/m at starting web masss g = 150 g/m^2 and thickness t = 2mm it is necessary to select the following parameters :

Forming teeth intersection ***P*** *= 4,5 mm*

Output velocity v_3 *= 2 m/min*

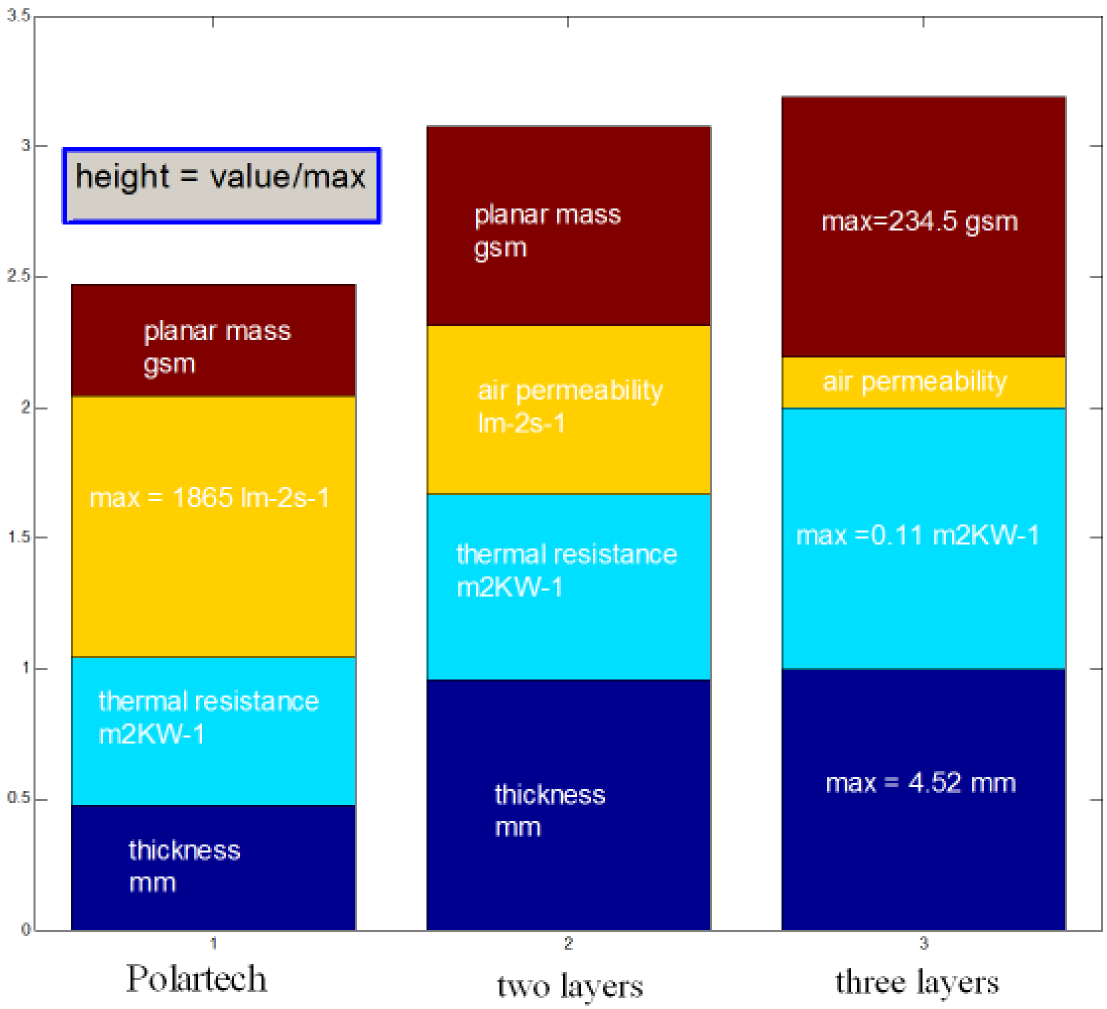
Input web densification K_n = 1.9

Three layer nonwovens: outer layers- spun bond with nanofibrous net, inner layer -FIBERTEX type Fiberback 80 CB. Before producing of final product were these layers joined by needle punching.



Three layer nonwovens: outer layers - FIBERTEX type Fiberback 80 CB, inner layer - POLAR alfa. Before producing of final product were these layers joined by needle punching.

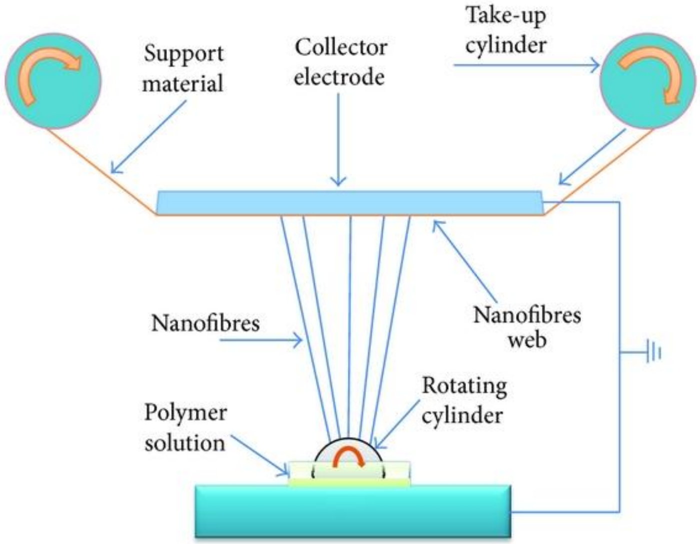
Enhancing insulation

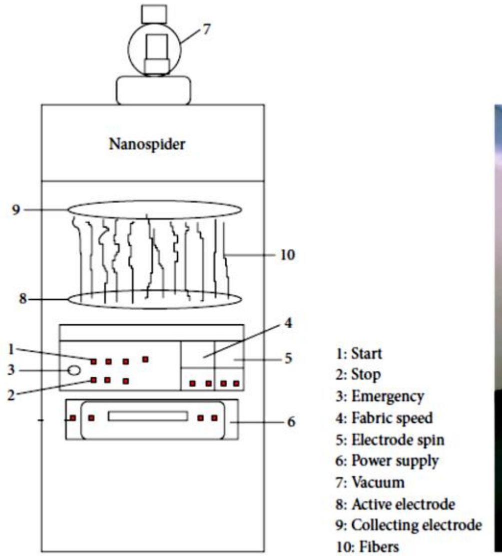


As insulation layer the *Polartec Alpha* (PES multifil, PES staple, PES/VS multifil)- *sample1* was selected. By Rotis technology the two- *sample2* and three- *sample2* layers composed from POP 1.5 dtex nonwoven web covering Polartec Alpha layer were prepared.

Nano layer preparation by electrospinning

Electrospinning was carried out using Nanospider technology. Nanospider laboratory machine NS LAB 500S from Elmarco s.r.o.





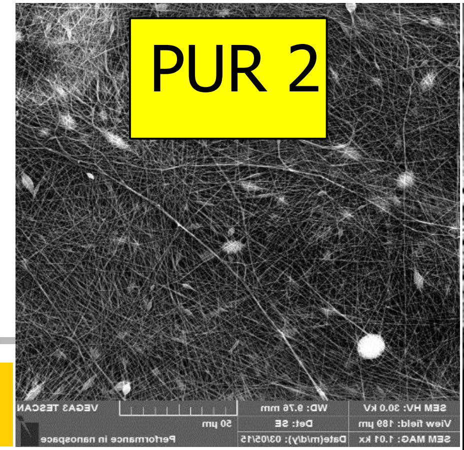
Schematic diagram of NS LAB 500S

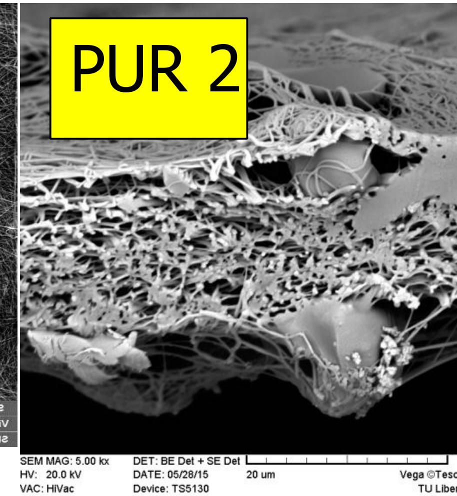
Nanospider; NS LAB 500S
Elmarco, Czech Republic

Jirsák, O. Sanetrník, F. Lukáš, D. Kotek, V. Marinová, L. Chaloupek, J. (2005) WO2005024101 A Method of Nanofibres Production from A Polymer Solution Using Electrostatic Spinning and A Device for Carrying out The Method

Nanospider Setting up

Production of PUR embedded with aerogel:



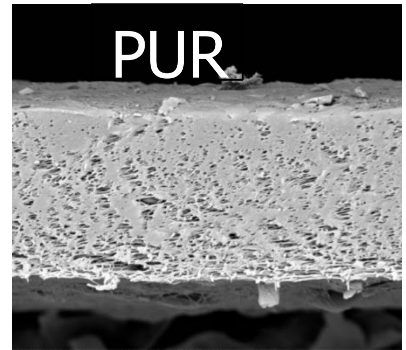


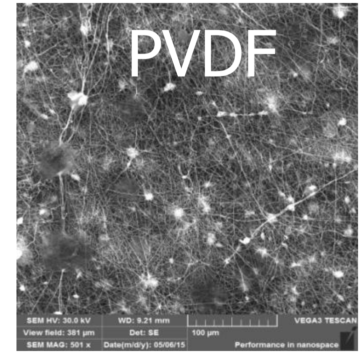
Parameters	Specifications
Distance of electrode	175mm
Wire speed	0,2mm/s
Substrate speed	15 mm/min
Carriage speed	380-430mm/s on 500mm distance
Substrate	SB blue
Voltage	-10/60kV
Size of the girder	ø 0, 7
Air flow	90/100m³h

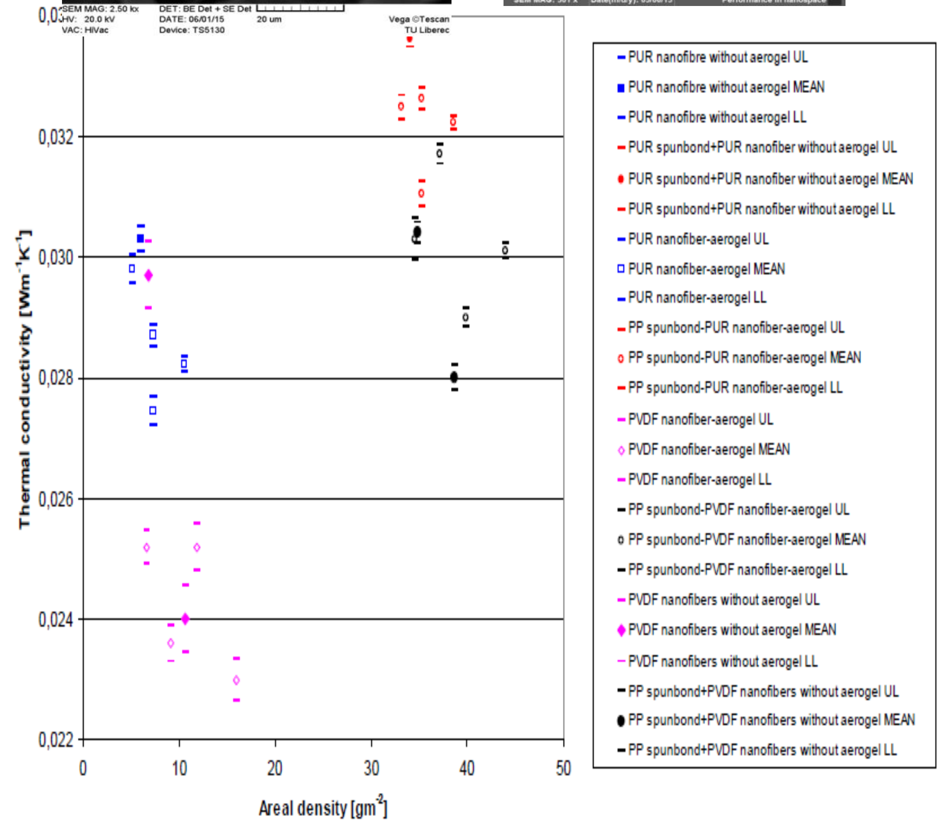
Samples	Air temperature and humidity	Size girder
PUR 1	22,7%/23°C	ø0, 7
PUR 2	20,3%/23,6°C	ø0, 7
PUR 3	20,8%/23,3°C	ø0, 7
PUR 4	23,1%/24,4°C 23,1%/24,2°C	ø0, 7/ ø 0,8/ ø 1,0
PUR 5	23,1%/24,8°C (First layer)	ø0, 9
	21,5%/26°C (Second layer)	ø0, 9

Nanofibers and aerogel

PU1	PUR nanofibers
PU2	PUR nanofibers + aerogel (Powder)
PU3	PUR nanofibers + aerogel (Granular)
PU4	PUR nanofibers + aerogel (Powder)
PU5	PUR nanofibers+ aerogel (Granular)
SPU1	PP spunbond+PUR nanofiber
SPU2	PP spunbond+PUR nanofibers + aerogel (Powder)
SPU3	PP spunbond+PUR nanofibers + aerogel (Granular)
SPU4	PP spunbond+PUR nanofibers + aerogel (Powder)
SPU5	PP spunbond+PUR nanofibers + aerogel (Granular)
PVDF1	only PVDF nanofibers
PVDF2	only PVDF nanofibers
PVDF3	PVDF nanofibers + aerogel (Powder)
PVDF4	PVDF nanofibers + aerogel (Powder)
PVDF5	PVDF nanofibers + aerogel (Granular)
PVDF6	PVDF nanofibers + aerogel (Granular)
SPVDF1	PP spunbond + PVDF nanofiber
SPVDF2	PP spunbond + PVDF nanofiber
SPVDF3	PP spunbond + PVDF nanofibers + aerogel (Powder)
SPVDF4	PP spunbond + PVDF nanofibers+ aerogel (Powder)
SPVDF5	PP spunbond + PVDF nanofibers + aerogel (Granular)
SPVDF6	PP spunbond + PVDF nanofibers + aerogel (Granular)







Powder – doped nanofiber

Granular – surface attachement on nanofiber

Textiles for high thermal insulation – three layer flat nonwovens

Nanovia A SMNF 57 60 gm^{-2}:

Outer layer: PP spunbond/meltblown 37 gm^{2}I

Inner layer: nanofibres layer of polymer PVDF

Outer layer: PP spunbond 20 gm^{2}

Thickness: **, 95% confidence interval 0,29-**

Thermal conductivity: 0,031 Wm^{-1}K^{-1}**, 95% confidence interval 0,030-0,032 Wm^{-1}K^{-1}**

Nanovia F EPA E 11 gm^{-2}**:**

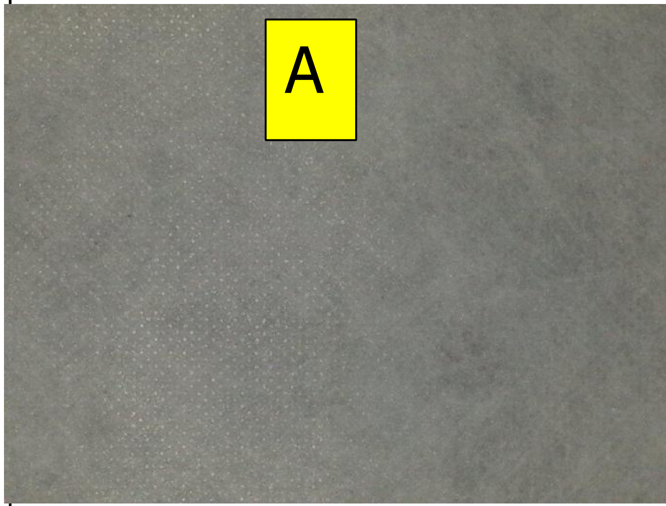
Outer layer: PP spunbond/meltblown 37 gm^{2}

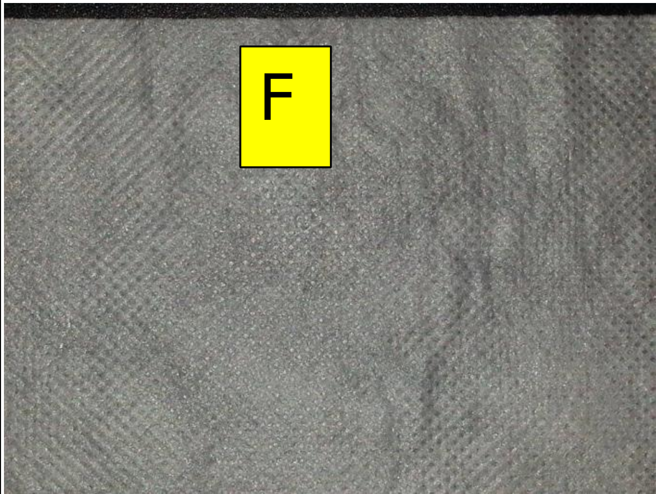
Inner layer: nanofibres layer of polymer PA6

Outer layer: PP spunbond 20 gm^{2}

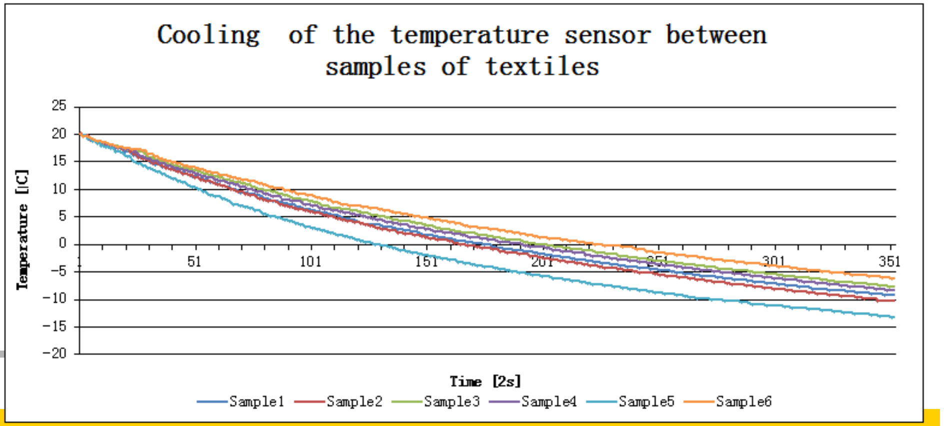
Thickness: **, 95% confidence interval 0,33-**

Thermal conductivity: 0,032 Wm^{-1}K^{-1}**, 95% confidence interval 0,031-0,033 Wm^{-1}K^{-1}**





Conclusion



(1) Thremal conductivity of fabric is mainly influenced by total fabric porosity

(2) Thermal insulation of fabric is governed by its thickness

(3) Perpendicularly laid nonwoven are useful for creation of sandwich type of insulation layer.

(4) Nano fibrous layers are suppressing radiation heat transfer component and presence of aerogels lead to supress concuctivity.

(5) The changes in fabric construction parameters are simple in the case of nonwovens but limited in the case of woven or knitted fabrics.

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