THERMAL COMFORT OF CLOTHING IN WET STATE

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PROJEKT OPTIS PRO FT, reg. č.: CZ.1.07/2.2.00/28.0312 JE SPOLUFINANCOVÁN EVROPSKÝM SOCIÁLNÍM FONDEM
A STÁTNÍM ROZPOČTEM ČESKÉ REPUBLIKY

- Thermal Comfort
- Modes of Heat Transport
- Skin Wetness
- Hygroscopicity of Fibres
- Water Vapour Transport
- Sweating
- Effect of Fabric Moisture Content on Thermal Properties

THERMAL COMFORT

Thermal comfort is defined as that condition of mind which expresses satisfaction with the thermal environment
(ASHRAE's*) defination Fanger 1982).

Thermal comfort implies the maintenance of the body temperature within relatively small limits (average skin temperature 32-34^{0}C). Under the conditions where the thermal comfort cannot be achieved by the human body's own ability (f. e. body temperature regulation), such as very cold or hot weather, **CLOTHING** must be worn to support its temperature regulation by:

- resisting,
- provide the heat exchange between the human body and the environment.

*) American Society of Heating, Refrigerating and Air Conditioning Engineers

Thermal Comfort

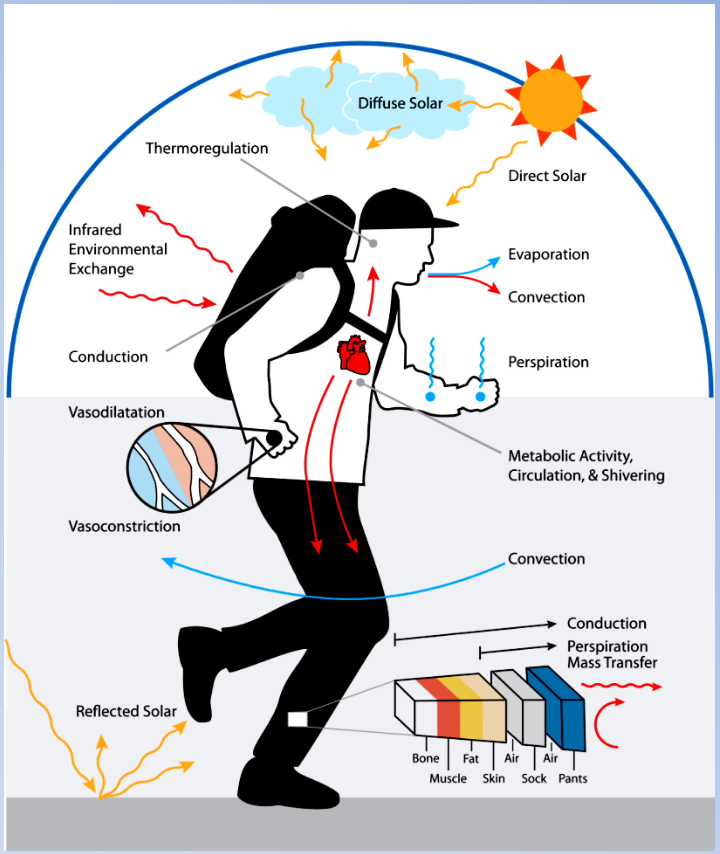
The factors that have relevant influence on the thermal comfort can be divided into two groups.

<u>1. Environmental factors:</u>

- Temperature
- Thermal Radiation
- Humidity
- Air Speed

<u>2. Personal factors:</u>

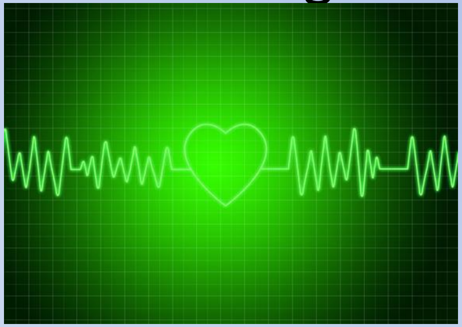
- Personal activity and condition
- Clothing



THERMAL COMFORT

The physiological conditions for general thermal comfort of person can be specified as follows (acc. Hensel 1981):

1. **the core temperature** (the deep central area including the heart, lungs, internal organs and brain) **within 36,6°C to 37,1°C** changes of more than **2°C** can be dangerous to human life;
2. **the average skin temperature**:
   - **within 33°C to 34.6°C for men**,
   - **within 32,5°C to 35°C for women**,
3. **temperature regulation active** and **completely realized by vasomotor control of blood flow to the skin**, i.e. no sweating and no shivering present.



THERMAL COMFORT

To achieve this consistency, heat production inside the human body and heat lost from the human body should be balanced.

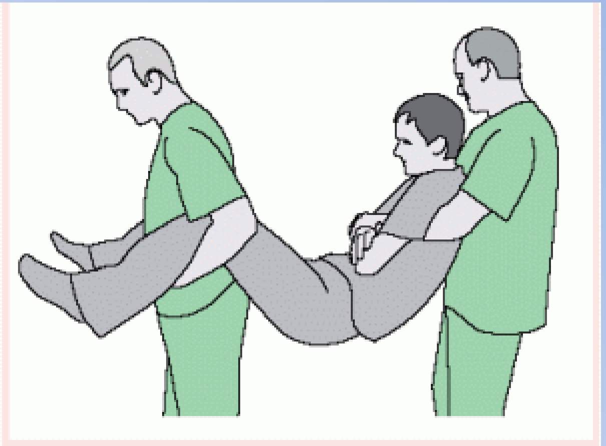
The human body's own ability to maintain this balance is by **TEMPERATURE REGULATION**.

In this process, heat lost from the human body is adjusted by:

- changing skin temperatures,
- sweating,
- heat production is modified by internal body activities.

The effect of temperature regulation is limited. If changes of heat lost and heat production are beyond the limits, the core temperature cannot be maintained and **life can be in danger**.

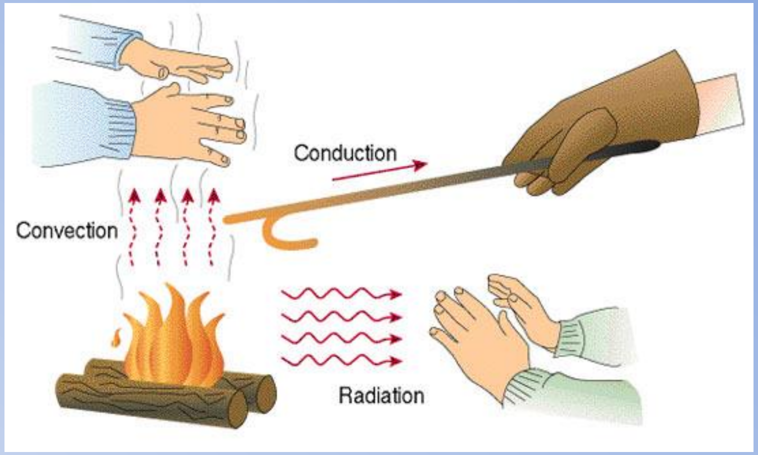
CLOTHING IS USED TO HELP THE BODY TEMPERATURE REGULATION.

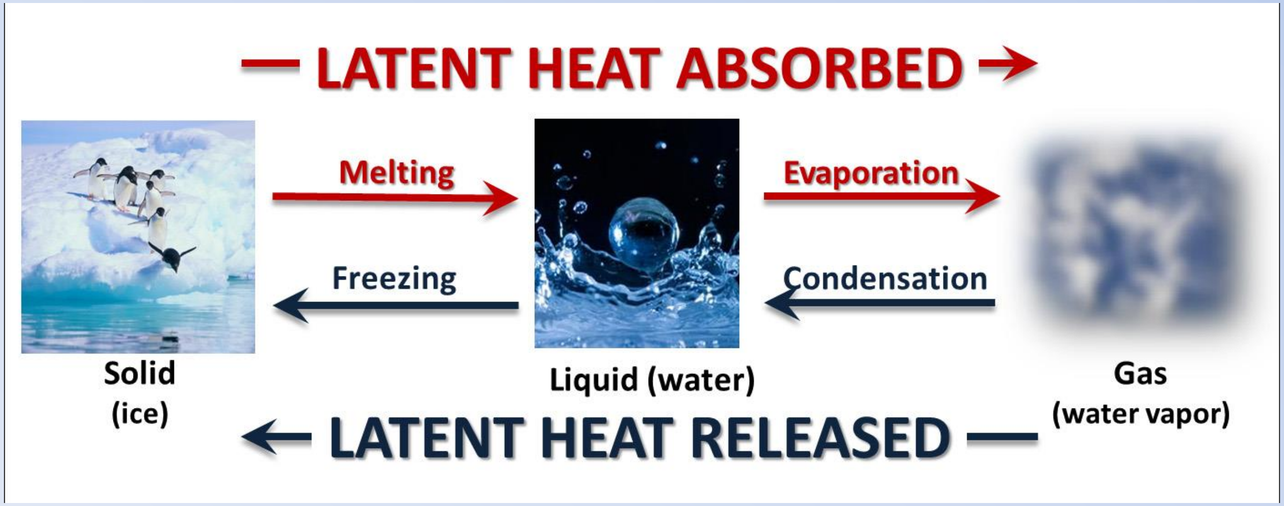


THERMAL COMFORT

Heat can be transferred through clothing by:

1. Conduction,
2. Convection,
3. Radiation,
4. Latent heat transfer by moisture transport..





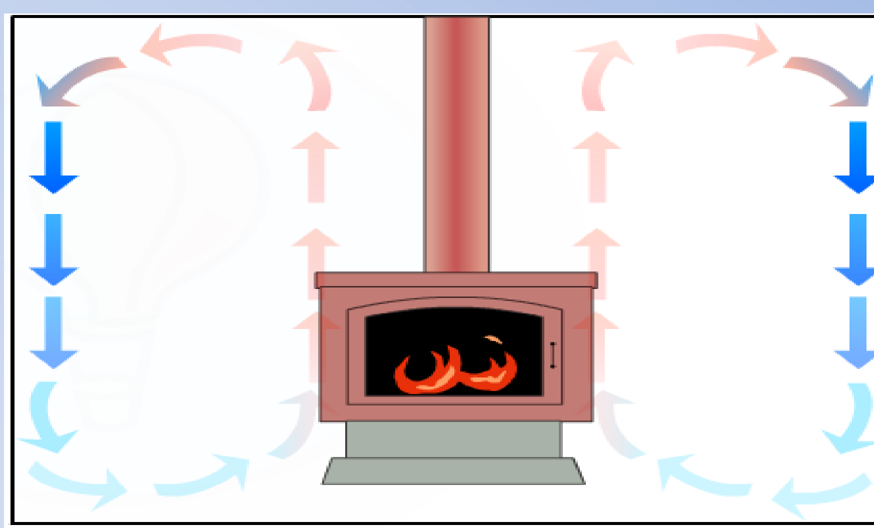
CONDUCTION

- Conduction is a process in which heat is transferred through a body or from one body to another without appreciable displacement of the parts of the body.
- Conduction is the up and down movement of gases and liquids caused by heat transfer.

When a gas or liquid is heated, it warms, expands, and rise because it is less dense.
When the gas or liquid cools, it becomes denser and falls.

From the molecular point of view, the conductive heat is transferred from a faster moving molecule of higher temperature to a slower moving molecule of lower temperature.

It creates a convection current.



Conduction

Principal relations describing the heat conduction:

Fourier's law, expressing the proportionality among of heat flow q[W/m^{2}K], thermal conductivity λ[W/m*K] and temperature gradient Δt/Δx:

$$q = - \lambda * \Delta t / \Delta x \qquad (1)$$

Thermal conductivity coefficient λ presents the amount of heat, which passes from 1 m^2 area of material through the distance 1 m within 1s and create the temperature difference 1 K.

In clothing systems, all components of clothing such as air, fibres and moisture vapor **are thermal conductors**.

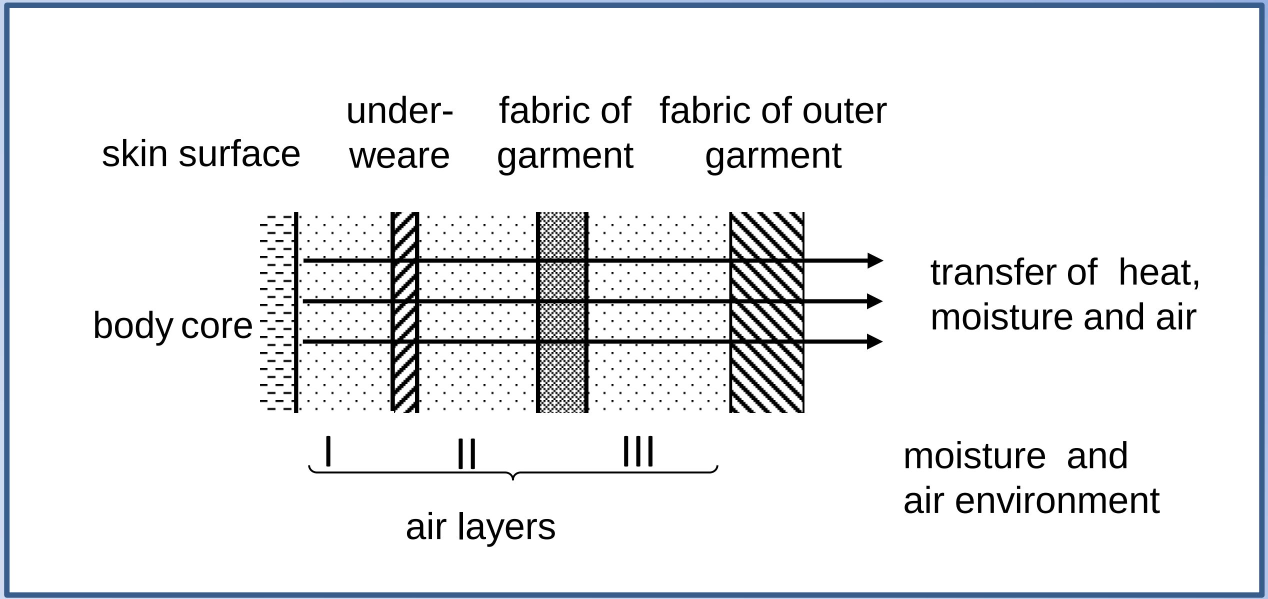
Relation for **thermal resistance R [m^{2}K/W]** of fabrics, thin air layers and other plane materials of thickness **h [m]**:

$$R = h / \lambda \qquad (2)$$

Thermal resistance of air layer in clothing reaches its maximum for h = 5mm.

CONDUCTION

Total thermal resistance of clothing $\mathbf{R_{CL}}$ consisting of full area individual layers: $$R_{CL} = R_1 + R_2 + R_3 + \ldots \qquad (3)$$



Total heat flow - heat power Q^*[W] through a clothing of area A_{CL} by conduction within the temperature gradient $\mathbf{\Delta t = t_S - t_E}$ is then given by the equation:

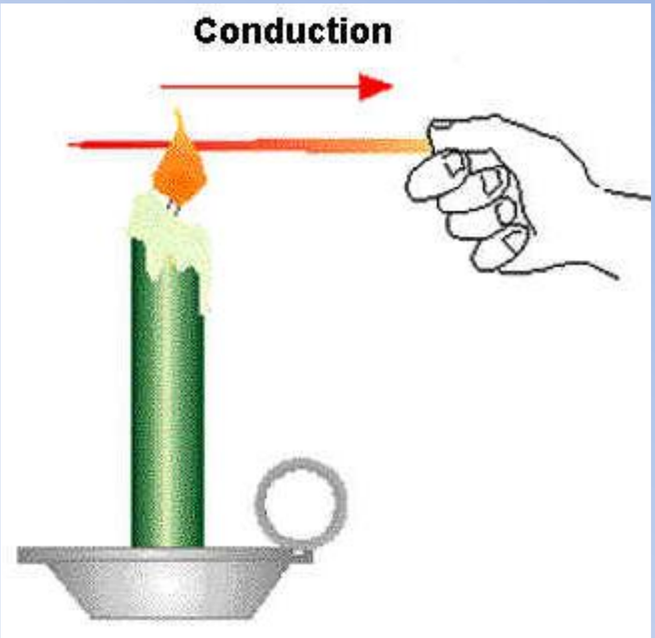
$$Q^* = A_{CL} \,.\, q = \Delta t \,.\, A_{CL} / R_{TOT} \qquad (4)$$

where $R_{TOT} = R_{CL} + R_E$

CONDUCTION

- Metals have the highest thermal conductivity (graphene 4840–5300 W/m*K, silver -429 W/m*K, gold - 317 W/m*K, steel - 58 W/m*K)
- Polymers have low thermal conductivity from 0.2 to 0.4 W/m*K.
- The thermal conductivity of textile structures is in the range from 0.033 to 0.01 W/m*K.
- Steady air is 0.026 W/m*K in temp 20 ^{0}C,
- Water is 0.6 W/m*K
- Salt is 6.5 W/m*K.

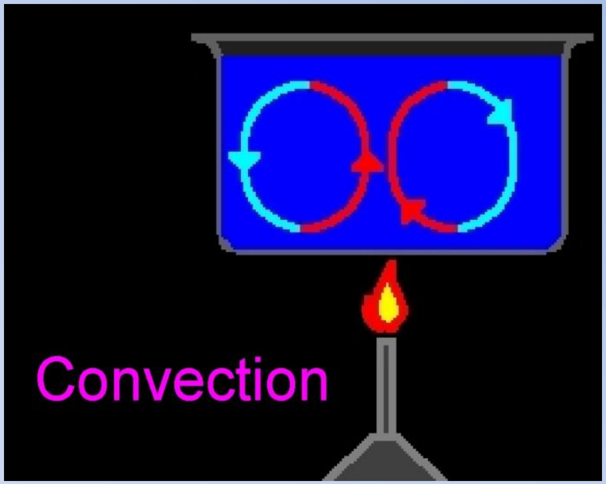
THEREFORE, THE PRESENCE OF WATER CAN ADVERSELY AFFECT ON TEXTILES!



Convection

Convection is the transfer of heat from one point to another within a fluid, gas or liquid, by the mixing of one part of the fluid with another. Heat is transferred by particles of fluids moving with the velocity v[m/s].

The motion of the fluid may be entirely the result of differences of density due to the temperature differences, as in **natural convection**;
or produced by an external force, as in **forced convection.**
The rate of convection depends on the motion of the fluid and the temperature gradient.



CONVECTION

The convection within clothing systems can be caused by:

- the differences of air density at different places,
- external wind
- body motion.

When the human body is moving or in strong windy conditions, ventilation is important way of convective heat transfer through clothing.

Ventilation is the exchange of generally hot, wet air within a clothing system and cold, dry air in the environment without passing through fabric layers (Mecheels 1977).

It could account for **75%** of the total heat loss from the human body when the wearer is walking in strong windy conditions (Keighley 1985).

CONVECTION

The heat transfer coefficient $\boldsymbol{\alpha_C}$ [W/m^{2}K] is relatively low for natural convection, and increases for forced convection.

For the typical conditions for the clothing use, the **heat transfer coefficient** can be calculated by a simplified equation:

$$\alpha_C = 8,3\ v^{1/2} \qquad (5)$$

where: v[m/s] – velocity of moving fluids.

The Newton's law for the **heat flow transferred** by any kind of convection is as follows:

$$q = \alpha_C\,(t_1 - t_2) \qquad (6)$$

Convection thermal boundary layer presents important **external thermal resistance**: $R_{boundary\ layer} = R_E$ (7)

which should be included into the **total thermal resistance** R_{TOT}

RADIATION

Radiation is the heat exchange between a hotter and a colder body by emitting and absorbing radiant energy.

Heat exchange by radiation depends only on the temperature and the nature of the surface of the radiating objects.

The heat exchange between two gray surfaces is:

$$\mathbf{Hr = \sigma * \varepsilon_1 * \varepsilon_2 * (T_1^4 - T_2^4) * A} \qquad \mathbf{(8)}$$

where:

Hr - the radiant heat exchange in [W],

σ - the Stefen-Boltzmann's constant, $\sigma = 5{,}67x1O^{-8}$ [W/m^2*K^4]

$\varepsilon_1 * \varepsilon_2$ - the emissivity of the two gray surfaces,

T_1 and T_2 - the absolute temperature of the two gray surfaces,

A - is the area of the two surfaces.

RADIATION

The radiant heat can transfer directly through clothing spacing from the skin surface into the environment and between clothing materials.

The emissivity (by Spencer-Smith 1976):

- skin is about 0,95,
- textile fabrics, e.g. cotton, wool lies between 0,95 and 0,90.

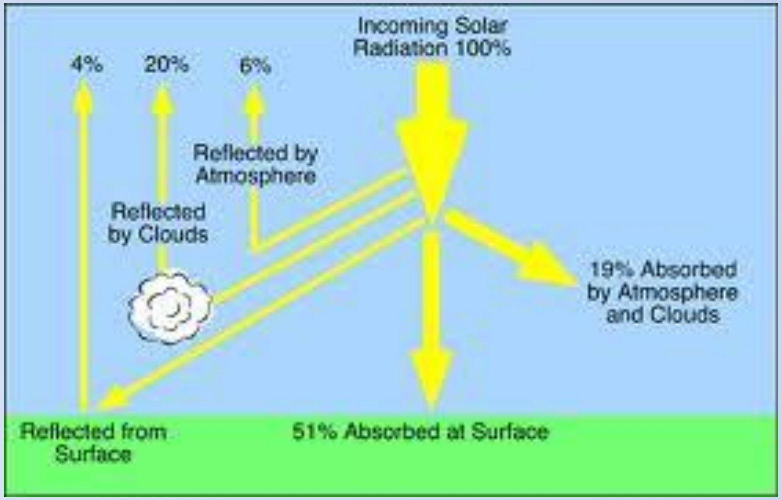
Radiation heat flow transferred between a dressed human of surface with absolute temperature $\mathbf{T_S}$ and a homogeneous, cooler environment of the average absolute temperature $\mathbf{T_E}$ is given by en expression:

$$q = \sigma\varepsilon_S \,(T_1^4 - T_2^4) \approx 4\sigma\varepsilon_S \,[(T_1 + T_2)/2]^3 \,(t_1 - t_2) \qquad (9)$$

For the thin or low density fabrics the portion of the heat transferred between the layers by infrared radiation may reach **10-30%** of the total heat flow.

RADIATION

Maximum level of heat flow coming from sun (equator, midday, no clouds): **1400 W/m²**.
Solar heat flow $\mathbf{q_S}$ in warm countries (Portugal, Spain, Italy) in summer midday: **900 W/m².**



The heat flow reaching a person dressed, depending on the angle of the sun rays and than can:

- some part of the flow be absorbed,
- some part - reflected
- the rest passes though the clothing.

THE DRY HEAT TRANSFER

The **dry heat transfer** through a clothing system can be described by

$$H_d = 1O * (Ts - Ta)/(Rc+Rs) \qquad (10)$$

Where:

Ts - the skin temperature(°C),

Ta - the ambient temperature(°C),

H_d - the rate of dry heat transfer through clothing (W/m^2),

Rc - the thermal insulation of the clothing,

Rs - the thermal insulation of the clothing surface.

Latent Heat Transfer

Latent heat transfer is a process in which heat is carried from one place to another by the movement of a substance which absorbs or dissipates heat by a change of phase.

Latent heat transfer is the only way of body cooling when heat produced inside the human body cannot be totally lost by conduction, radiation and convection.
In this case, **sweat is produced** at the surface of skin and heat is lost by evaporation of liquid sweat into moisture vapour which then passes into the environment.

Latent heat transfer is achieved by moisture transmission which is drove by the difference in partial water vapour pressure between the skin surface and the environment.

Latent Heat Transfer

The **latent heat transfer** through a clothing system can be described by:

$$Hl = c*(Ps - Pa)/ (Wc + Ws) \quad (11)$$

where,

Hl - the rate of latent heat transfer through clothing (W/m^2),

Ps - the partial water vapour pressure at the skin surface,

Pa - the partial water vapour pressure in the environment,

c - the evaporative heat at the skin temperature, c =2,44 KJ/g at 35°C,

Wc - the resistance to water vapour transfer of the clothing,

Ws - the resistance to water vapour transfer of the clothing surface.

Simultaneous Dry and Latent Heat Transfer

When dry and latent heat transfer exist at the same time the overall heat transfer **H** can be estimated by:

$$H = 10(Ts - Ta)/ (Rc+Rs) + c(Ps - Pa)/(Ws+Wc) \qquad (12)$$

In the above formula dry and latent heat transfer are treated independently - **it is the main principles involved in the heat transfer through clothing.**

Simultaneous Dry and Latent Heat Transfer

Under many circumstances, the heat transfer may be reduced due to the effect of **BUFFERING** and **CONDENSATION** (Spencer-Smith 1976).

BUFFERING happens when clothing materials absorb or desorb moisture vapour from the boundaries.

The effect can affect the thermal comfort of a wearer when his environmental condition suddenly will change,

f. e.: moving from dry, warm indoor into cold, wet outdoor, or when starts sensible perspiration.

SIMULTANEOUS DRY AND LATENT HEAT TRANSFER

Condensation happens when the partial water vapour pressure within the clothing is higher than the saturated pressure on the outside, determined by the local temperature.

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Condensation can result in extra chill for a person in a cold environment, and therefore should be eliminated as much as possible!

layers of clothing, some of this condensed moisture may return to the inner, warmer layers where it can be re-evaporated. This water vapour will later re-condense in the cooler layers.

This cycling of moisture between warmer and cooler parts of the clothing provides an **extra mode of heat transfer** between the body and the environment.

Skin Wetness

The latent heat lost is affected by the skin wetness.

The following equation describes this effect (by Mecheels & Umbach):

$$Hl = d(Pss - Pa)/W \qquad (13)$$

where:

Hl - the latent heat transfer by evaporation,

Pss - the saturated water vapour pressure at the skin surface,

Pa - the ambient partial water vapour pressure,

W - the resistance to water vapour transfer of the clothing system,

d - so-called "perspiration discomfort factor", „d" is directly related to the skin wetness.

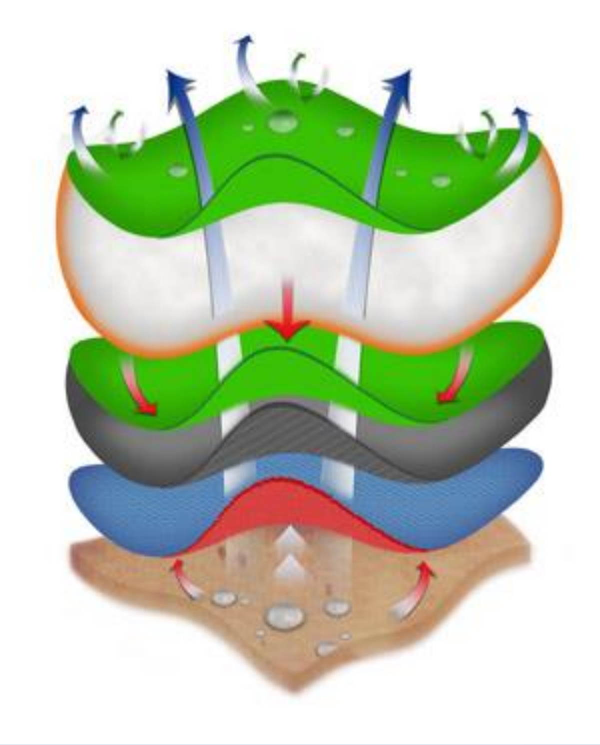
d = 0,1 when the perspiration is insensible,

and d = 1,0 when the skin is totally wetted.

SKIN WETNESS

The skin wetness can also affect the dry heat transfer because the absorption of liquid sweat or moisture by clothing materials :

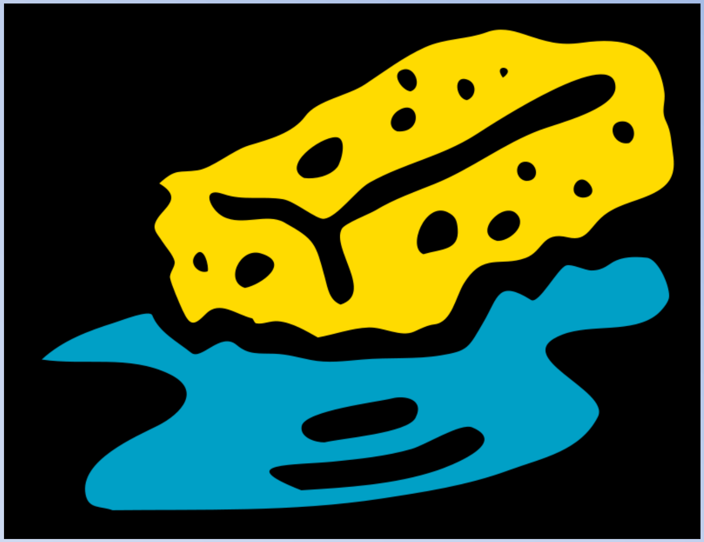
- can change the thermal properties of the materials,
- can induce a buffering effect,
- even can induce the condensation..



How Our Clothing Becomes Wet

As a result of the ability of fibres to the water sorption, which depends on:

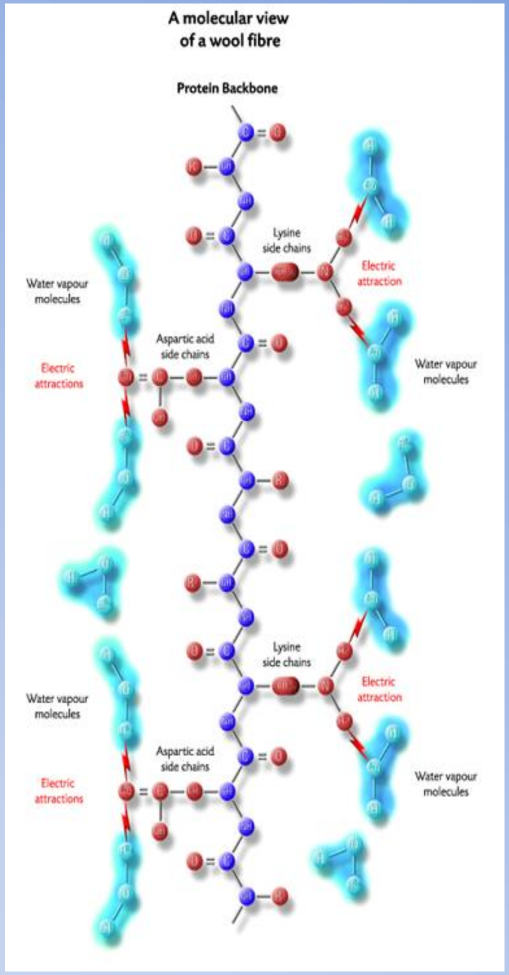
- molecular structure,
- super-molecular structure (degree of crystallization, internal orientation and cross-linking of the polymer)
- the macrostructure of the fibre..

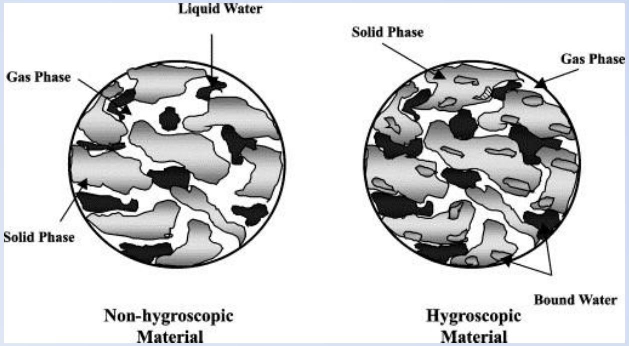


Hygroscopicity of Fibres

Hygroscopicity :

- is due to the presence of the polymer hydrophilic groups, such as: -OH,-COOH,-NH;
- is due to macrostructure fibre: micro-capillary, chink, holes, cracks;
- depends on the size and type of the surface of the fibres;
- depends on the presence of crystalline regions, which do not have the capacity to bind water.





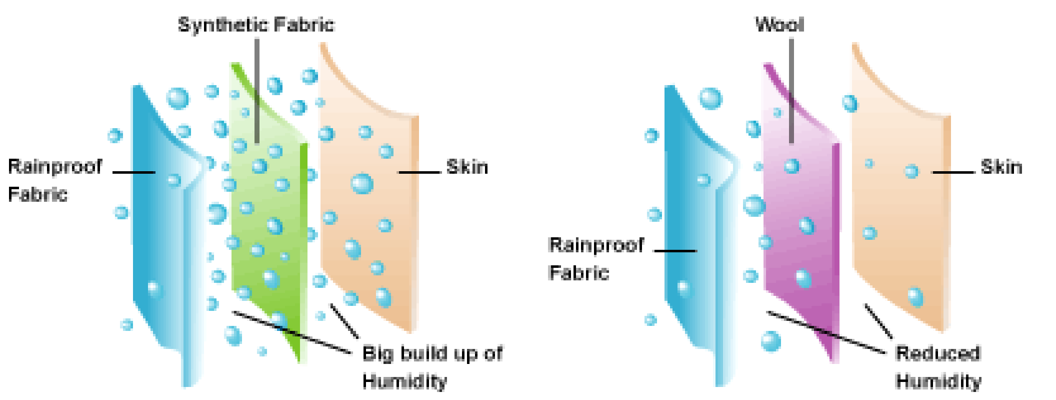
HYGROSCOPICITY OF FIBRES

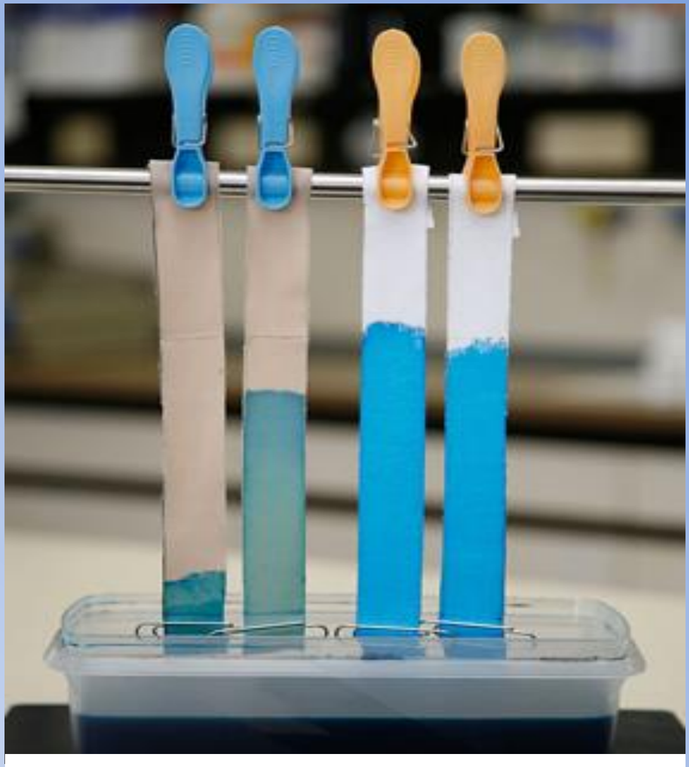
The fibres can be divided into:

1. **Hydrophilic** - refers to substances that absorb water.
2. **Hydrophobic** -hate water and repel it.

FIG 2: SYNTHETIC VS MERINO - ABILITY TO ABSORB MOISTURE

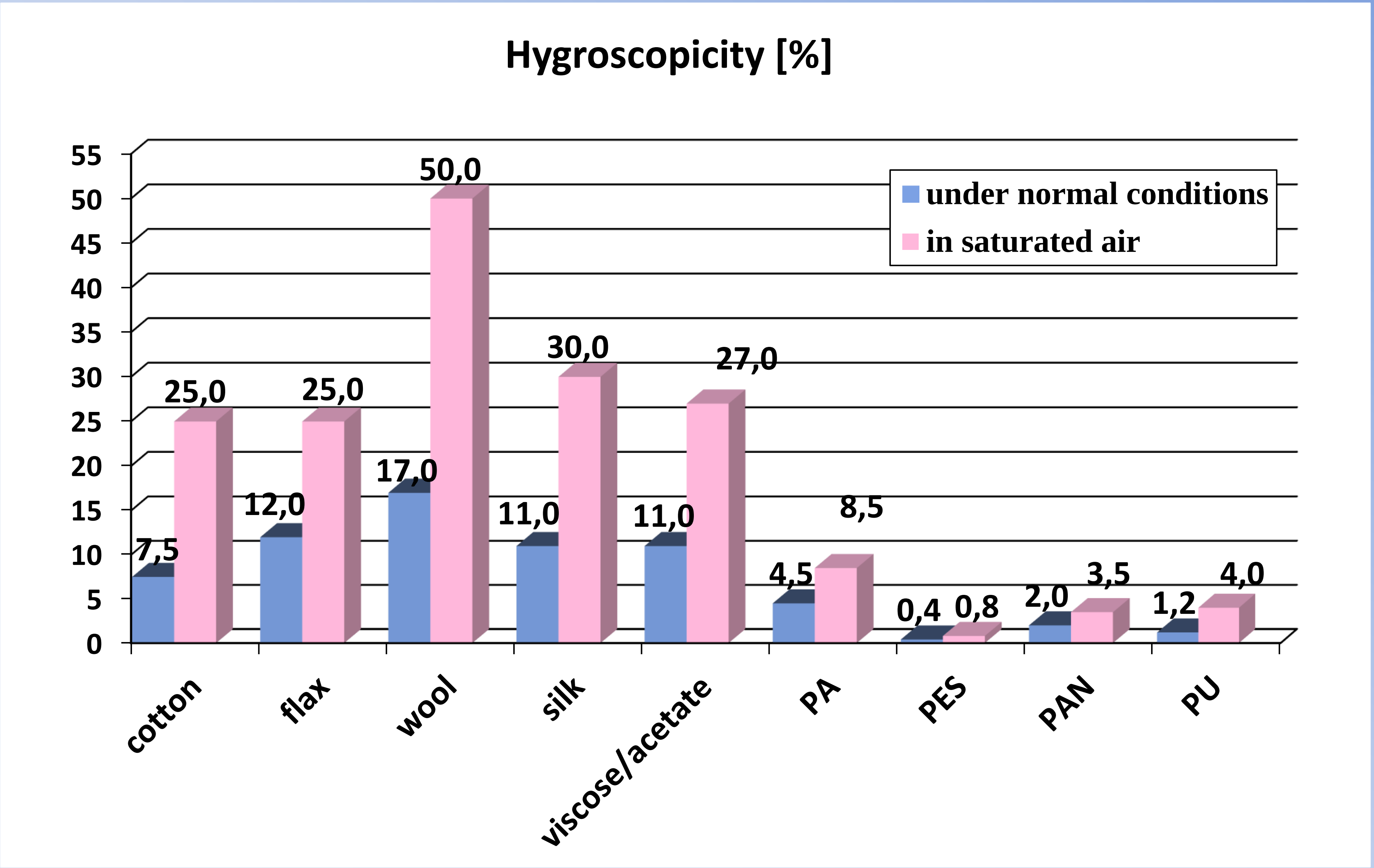
Synthetic fibres absorb very little moisture. Wool absorbs moisture vapour readily.





Samples 1 and 2 are made of polyester, 3 and 4 of cotton. 2 was treated with WETSOFT® NE 430.
Polyester is rendered hydrophilic.
Cotton stays hydrophilic.

HYGROSCOPICITY OF FIBRES



WATER VAPOUR TRANSPORT

Sweat is discharged by:

- ✓ diffusion,
- ✓ absorption,
- ✓ desorption,
- ✓ fibres wetting,
- ✓ capillary condensation,
- ✓ air exchange rate of the layers around body skin.

Transport of water vapour is characterized mostly by three indicators:

1. Water vapour transmission resistance (Ret), expressed in [m^2Pa/W];
2. Water vapour permeability (MVT), expressed in [g/m^2*24];
3. Flow of water vapour, expressed in [g/24h].

Water Vapour Transport

According parameter of Water Vapour Transmission Resistance (Ret) textile fabrics can be classified into:

- **Class 3** – textile fabric with the resistance **Ret ≤ 20 [m^2Pa/W]** is considered as very good permeable,
- **Class 2** - textile fabric with the resistance **Ret = 20-150 [m^2Pa/W]** is regarded as moderately permeable,
- **Class 1** - textile fabric with the resistance **Ret ≥ 150[m^2Pa/W]** is regarded as impermeable and does not provide any comfort.

The Factors which Decide on Water Vapour Permeability:

- ✓ thickness,
- ✓ volumetric mass,
- ✓ filling,
- ✓ kind of fibres,
- ✓ temperature difference on both sides of the garment,
- ✓ relative humidity on both sides of the garment,
- ✓ speed of the air motion.

Approximate values of water vapor transport for clothing fabrics:

THE KIND OF TEXTILE MATERIALS	Water vapour resistance Ret [Pa*m^2/W]	Water vapour permeability MVT [g/m^2 *24h]	Flow of water vapour [g/24h]
Cotton knitted fabric	5	5000	12 000
Polyester fabric with sq. mass above 110 g/m^2	4 – 5	1800	4320
Polyamide fabric with sq. mass above 55 g/m^2	3 - 5	1860	4464
Polyester fleece knitting fabric (Polar) with sq. mass 100–200 g/m^2	13,4 – 23	1850	4440
Laminate with the breathable membrane	11 – 34	2000 – 8000	4800 – 19200

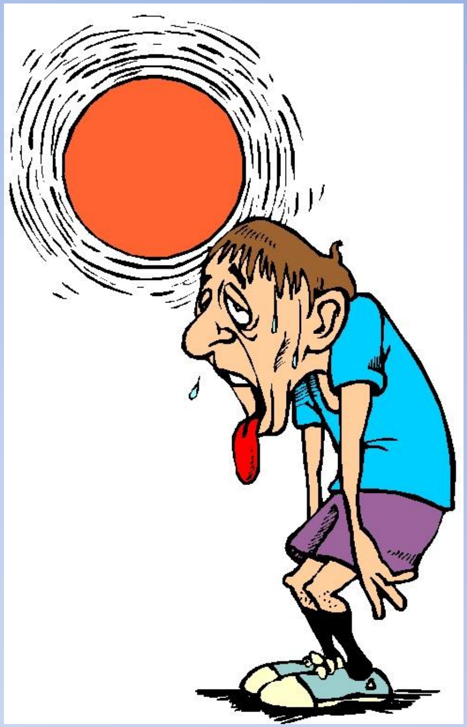
Why Our Clothing Becomes Wet

1. Due to the absorption of moisture evaporated from the body (high humidity of the internal environment: sweating, perspiration)

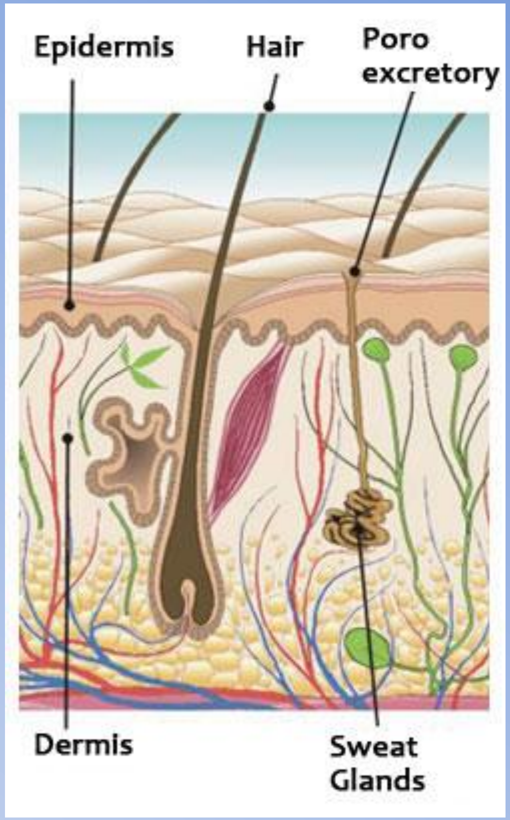
2. Due to the absorption of moisture from the outside environment (high humidity of the external environment: rain, snow, fog, e.g.)

Some Major Information About Sweating

- Sweating is the body's way of moderating internal temperature as a result of release the salty liquid from the body's sweat glands.
- This process is also called perspiration.
- Sweat is secreted from pores in the skin and then evaporated from the surface of the skin.
- This process of evaporation radiates energy away from the skin, cooling the body down.
- Sweating is an essential function which helps human body stay cool.
- Sweat is commonly found under the arms, on the feet, and on the palms of the hands..



Some Major Information About Sweating



- A person is born with about 2 to 4 million sweat glands. The glands start to become fully active during puberty.
- Women have more sweat glands then men, but men's glands are more active.
- Because sweating is the body's natural way of regulating temperature, people sweat more when it's hot outside.
- People also sweat more when they exercise, or in response to situations that make them nervous, angry, embarrassed, or afraid.
- Sweat in itself doesn't actually smell. Body odour is caused by the waste products of bacteria that are found naturally on the skin, which thrive in humid warm environments, therefore odour being more noticeable under the arms.

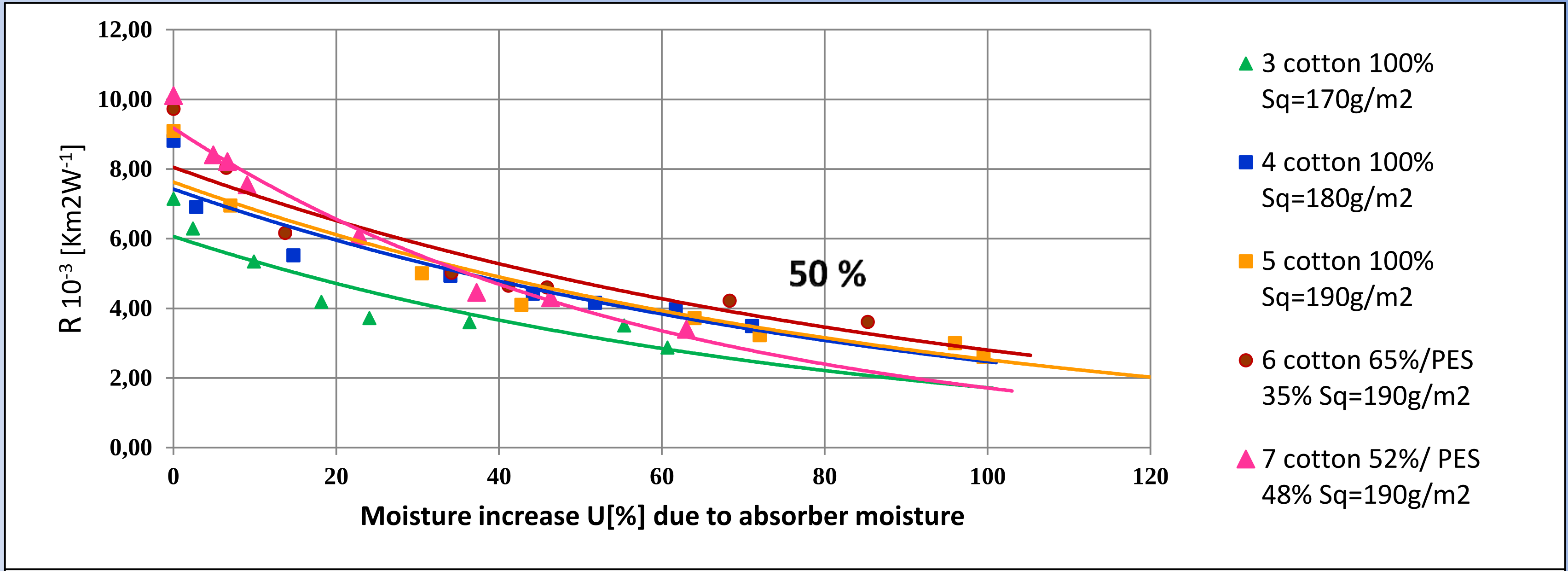
Sweat Production By Human Organism:

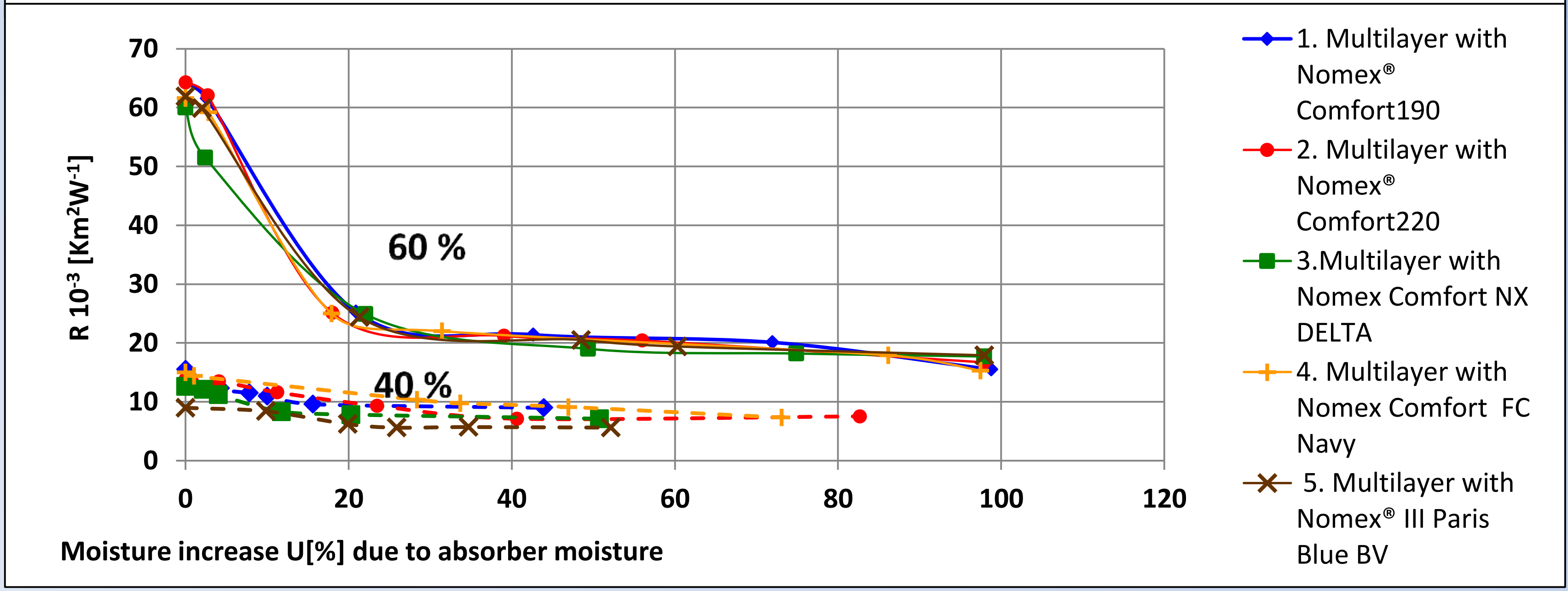
- under normal conditions in the state of rest (sleep, sitting - called the normal human perspiration) the amount of sweat is from **40 to 100 g/h** (960 ÷ 2400 g/24h);
- during the walk, the amount of sweat stands at level **65 ÷ 170 g/h** (1500 – 4000 g/24h);
- in the case of very intensive walk (in mountains) the amount of sweat may be increased **to 1600 g/h** (38 000 g/24h);
- with the hard physical work capacity of sweat can be **up to 1875g/h** (1,8 litres), it means that during 3 hours race rider secretes from the body approximately **5,5 litres** of sweat.

What happend when Our Clothing Becomes Wet

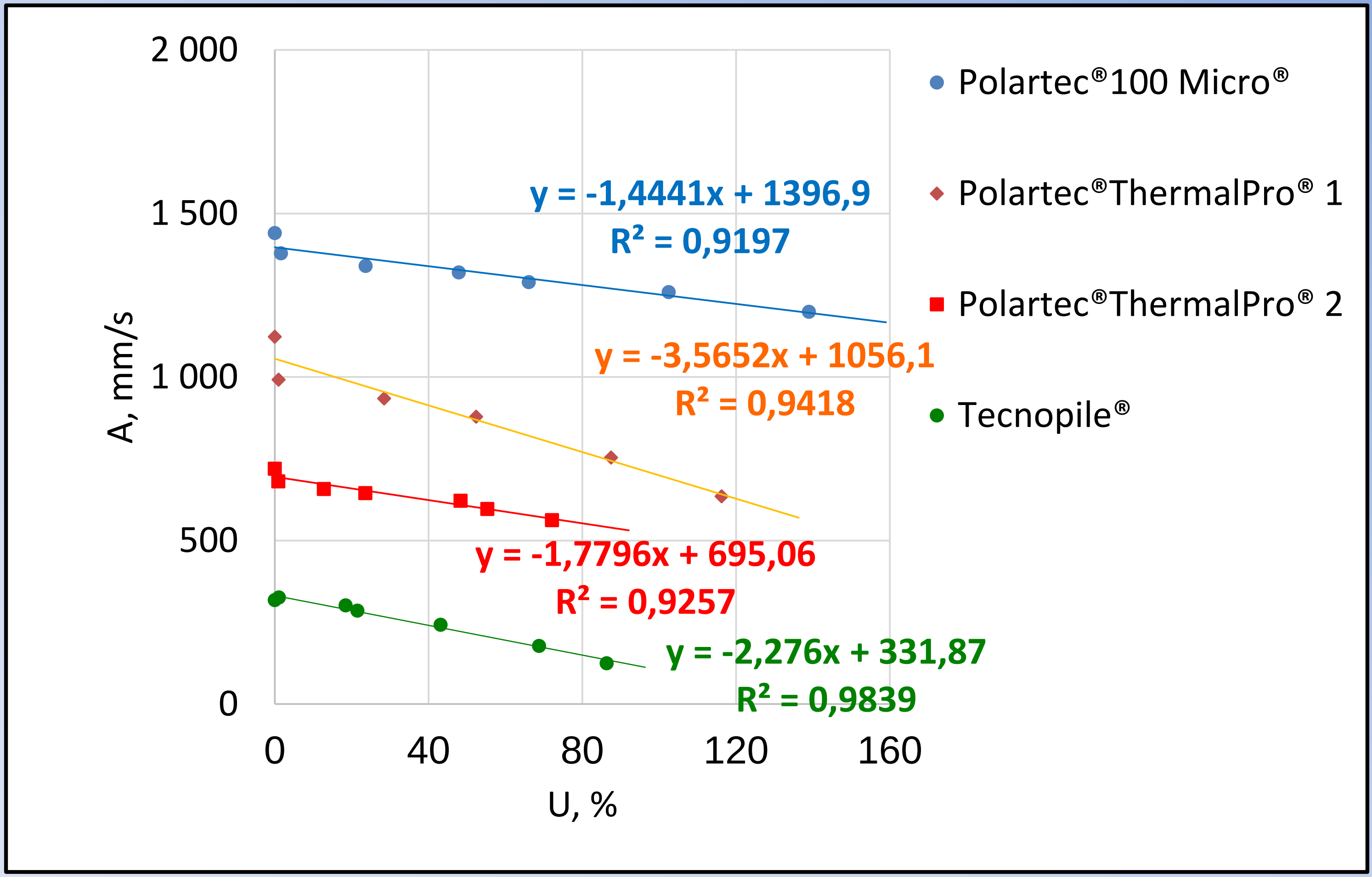
1. Clothing Insulation Decreases
2. Reduced Ability to Breathe
3. Air Permeability is Reduced
4. Water Vapour Permeability Decreases

Effect of Fabric Moisture Content on Thermal Resistance





Effect of Fabric Moisture Content on Air Permeability



Humidity and Insulation

% of Water in Air	Conductance ($Wm^{-1}K^{-1}$)	Increase in Conductance	% of Insulation of Dry Air
Dry air	0.025	1x	100%
10%	0.083	3.3x	30.3%
20%	0.140	5.6x	17.8%
30%	0.198	7.9x	12.7%
40%	0.255	10.2x	9.8%
50%	0.313	12.5x	8.0%
60%	0.370	14.8x	6.8%
70%	0.428	17.1x	5.8%
80%	0.485	19.4x	5.1%
90%	0.543	21.7x	4.6%
All water	0.600	24x	4.2%

Humidity and Insulation

Wet skin could significantly increase the effect of chilling body and decrease the time for frostbite.

The moisture content of the level **10-20%** could causes of drop in thermal insulation **up to 30%** compared to the dry fabric.

In 50% water and the insulation value is only 8%!

This is because water conducts heat 24 times more than dry air!

Thermal Comfort of Clothing in Wet State

Thank You For Your Attention!

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