Polymer Photonic Crystal Membrane for Human Body Thermoregulation

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Presenter

Mohamed Boutghatin, PhD student at the IEMN laboratory in France. The supervisors of my thesis work are: Yan Pennec and Vincent Thomy. The subject of my thesis is dealing with a new generation of textiles capable of regulating the temperature of the skin in order to maintain thermal comfort. The study is based on analytical calculations and numerical simulation codes using proven calculation methods such as the Finite Element Method (FEM). The theoretical study is followed by the fabrication of membranes in a clean room using high-performance nanotechnology methods and equipment.

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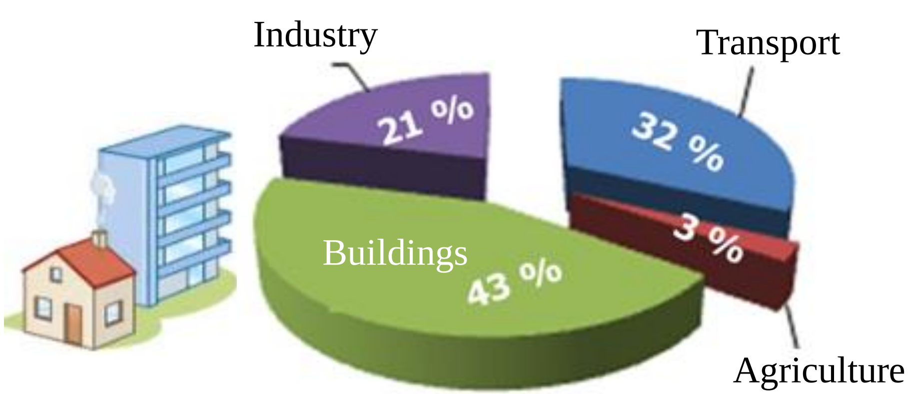
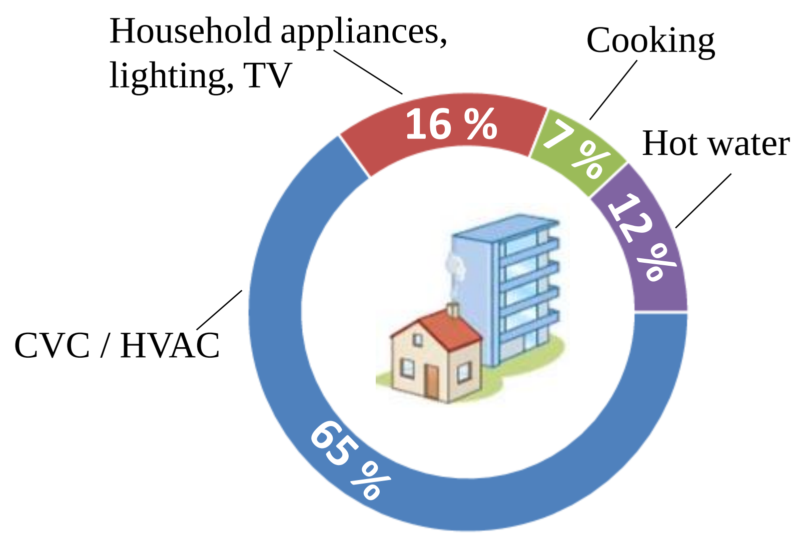
Context

Energy consumption by business sector



Distribution of energy used in building



CVC / HVAC predominate

How to reduce this consumption ?

How the human body exchanges heat with the environment ?

ADEME. Chiffres clés du bâtiment,2017

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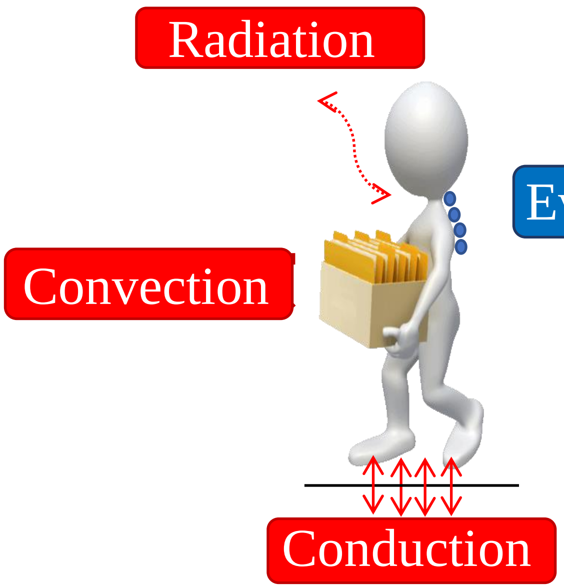
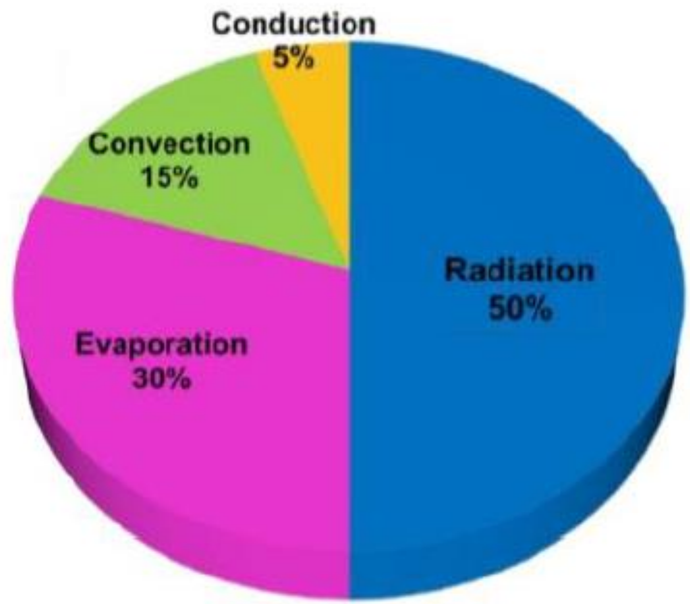
Context

Mechanisms of heat transfer by the human body



A. Marolleau, Étude des mécanismes d'interaction sous-vêtement/peau pour concevoir des textiles innovants en optimisant le confort au porté, l'Université des Sciences et Technologies de Lille 1, 2019.

Distribution of the different mechanisms



Radiative transfers predominate

Vanggaard L, Paulev PE, Zubieta-Calleja G. Thermo-regulation temperature and radiation. Medical Physiology and Pathophysiology: Essentials and Clinical Problems. Editors: Zubieta-Calleja, G., and Paulev, PE. 2011.

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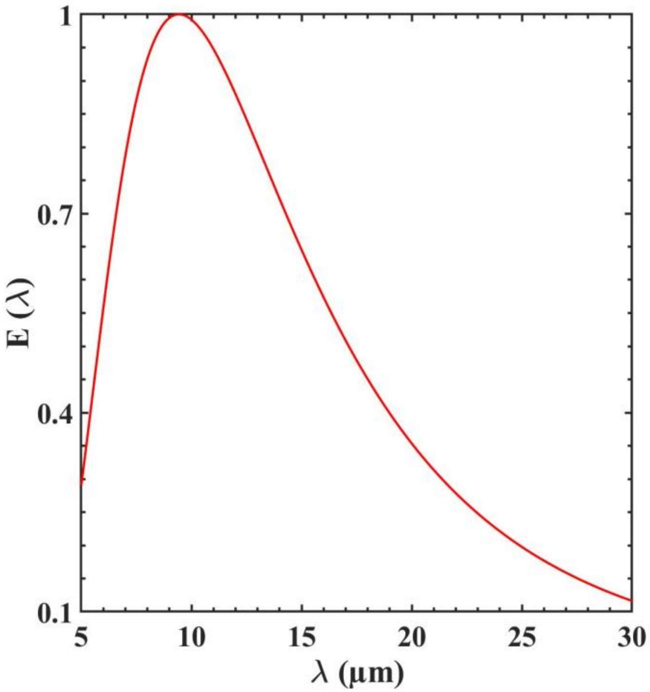
Context

The human body is assimilated to a black body. The emissivity of the human skin at 34 °C is given by Planck's law:

$$L^0 = \frac{2hc^2}{\lambda^5} \cdot \frac{1}{e^{hc/(\lambda kT)} - 1} \text{ en W.m}^{-3}\text{.sr}^{-1}$$

Normal emissivity in the range [5-30 µm]



- More than 50 % of radiation is emitted in the mid-infrared range [5-15 µm].
- Human skin at 34 °C emits a maximum of radiations at the wavelenght 9.5 µm.

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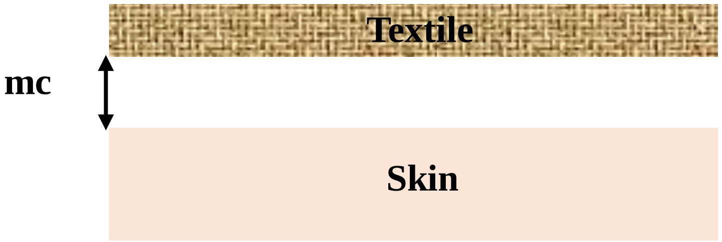
Objective

What do we want ?

Maintain the thermal comfort ($T_s = 34\ °C$) of human body in indoor areas

Replace the common strategy (heating/cooling building) by a new approach, called « personal thermal management »

Control the temperature of the space between the human skin and the textile, called microclimate (mc)



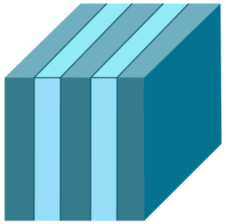
Tong J.K. et al, ACS Photonics, 2015

How ?

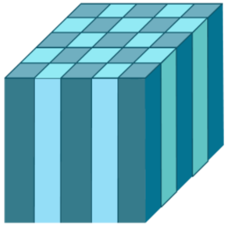
Modulate the human body radiations by using the photonic crystal properties in the mid infrared [5-15 µm]

Structure the garment to control the reflectance and transmittance in the mid-infrared range

One-dimensional photonic crystal (1D)



Two-dimensional photonic crystal (2D)



Li W. and Fan S., Opt.Express, 2018

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Outline

- Geometry and model
- Optical properties of polyethylene (PE) polymer
- Thermal balance
- Conclusions and futur work

Outline

Geometry and model

Optical properties of polyethylene (PE) polymer

Thermal balance

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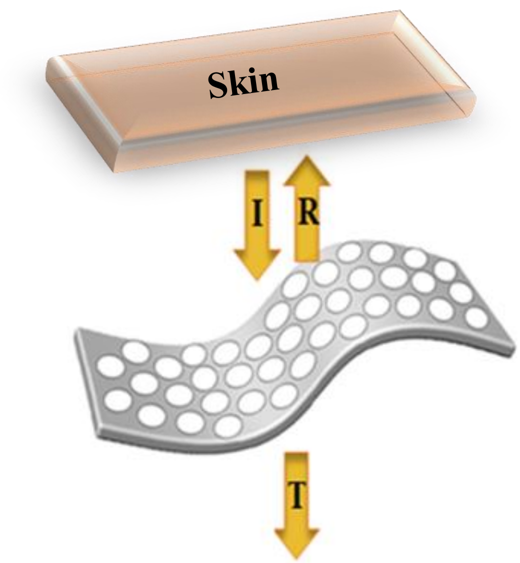
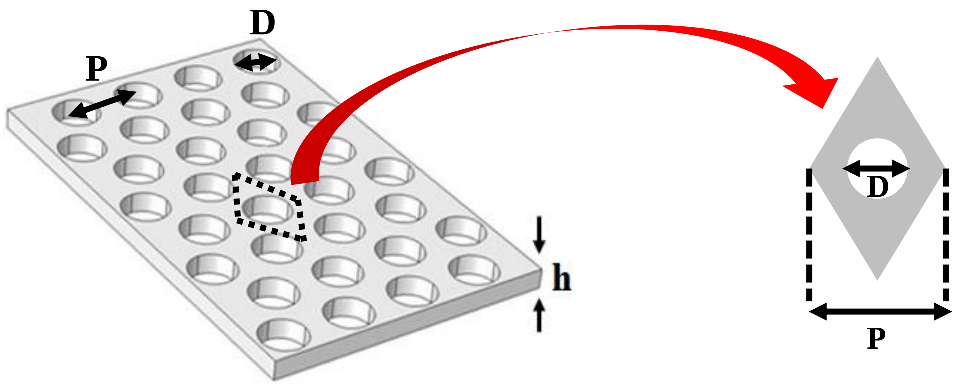
Geometry





Polymer membrane under human body radiation from the skin

3D view of the polymer membrane of thickness **h**, drilled with a triangular array of air holes with period **P** and diameter **D**.

In-plane view of the elementary unit cell

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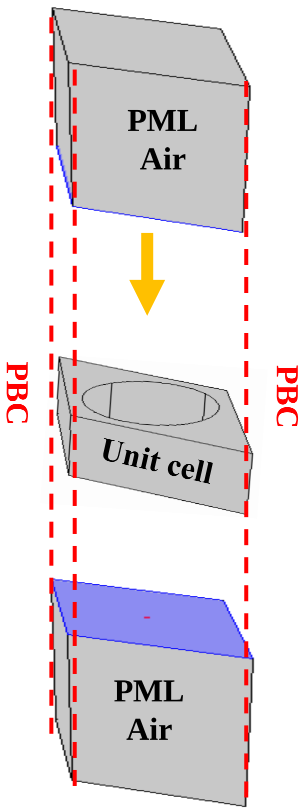
Model

3D view



Maxwell equation :

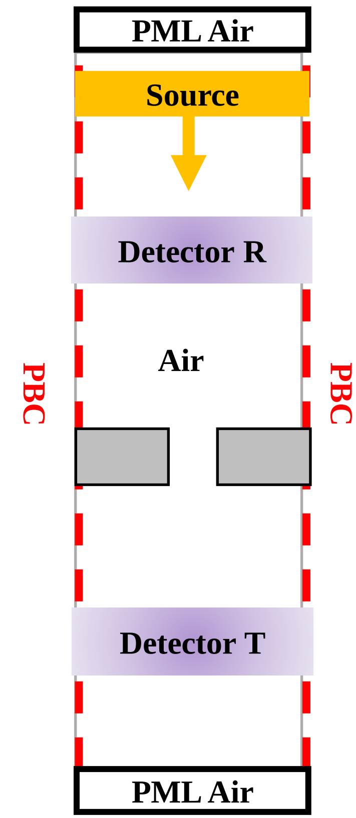
$$\nabla \times (\varepsilon_r^{-1} \nabla \times H) = (\frac{\omega}{c})^2 H$$

$$\nabla \times (\nabla \times E) = \varepsilon_r (\frac{\omega}{c})^2 E$$

FEM method by using commercial COMSOL software

- PML: Perfectly Matched Layers
- PBC: Periodic Boundary Condition

2D view



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Outline

Geometry and model

Optical properties of polyethylene (PE) polymer

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Conclusions and futur work

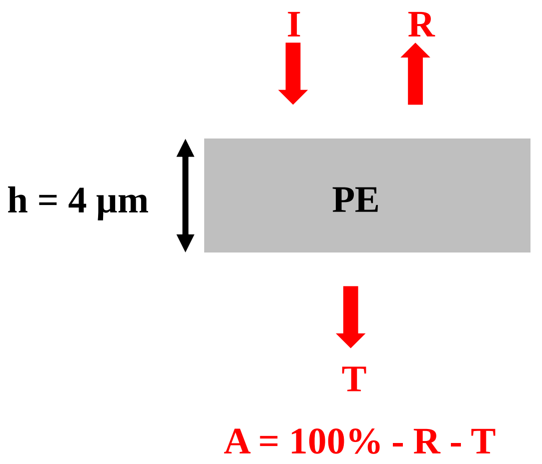
Polymer membrane

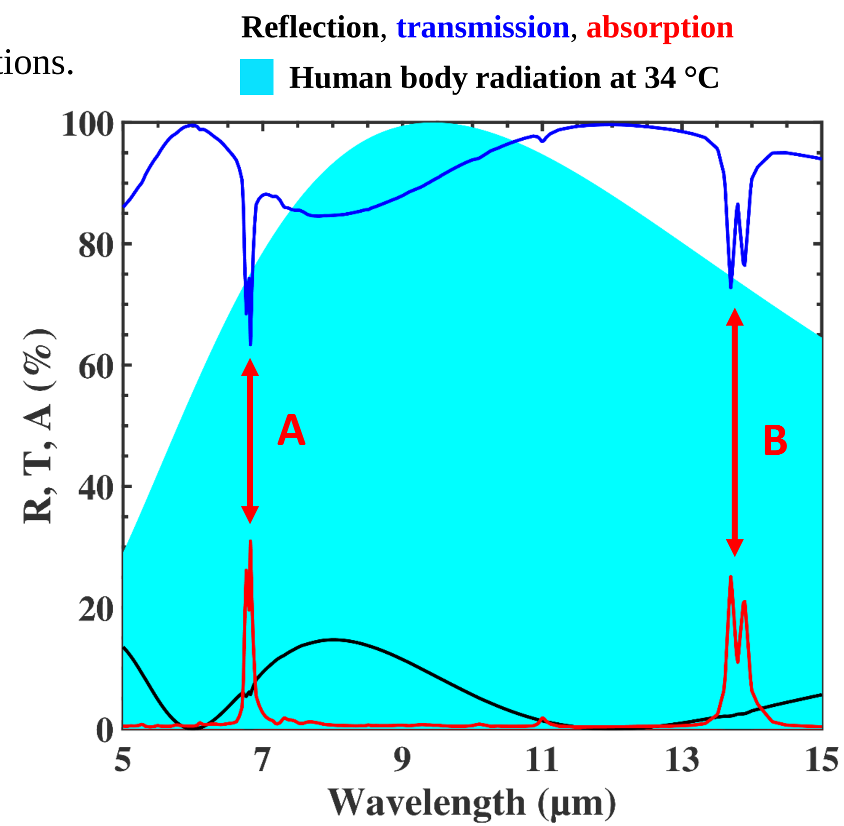
- **Polyethylene (PE)**

Thermoplastic polymer, used in a wide range of applications.

It is textile compatible.

Intrinsically transparent in the mid-infrared 5-15 µm.





A and B are intrinsic absorption peaks of PE around 7 µm and 14 µm respectively

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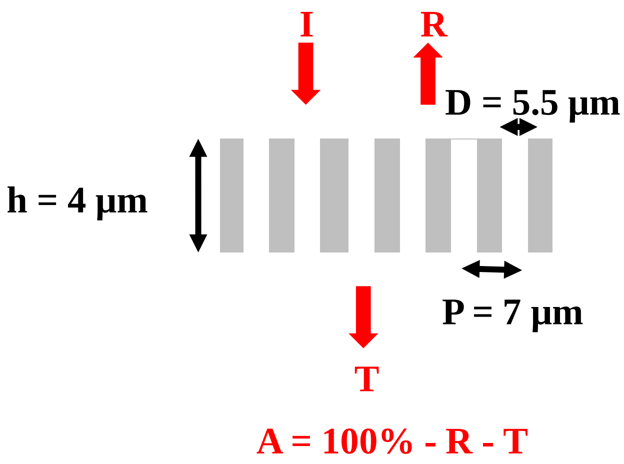
Structured membrane

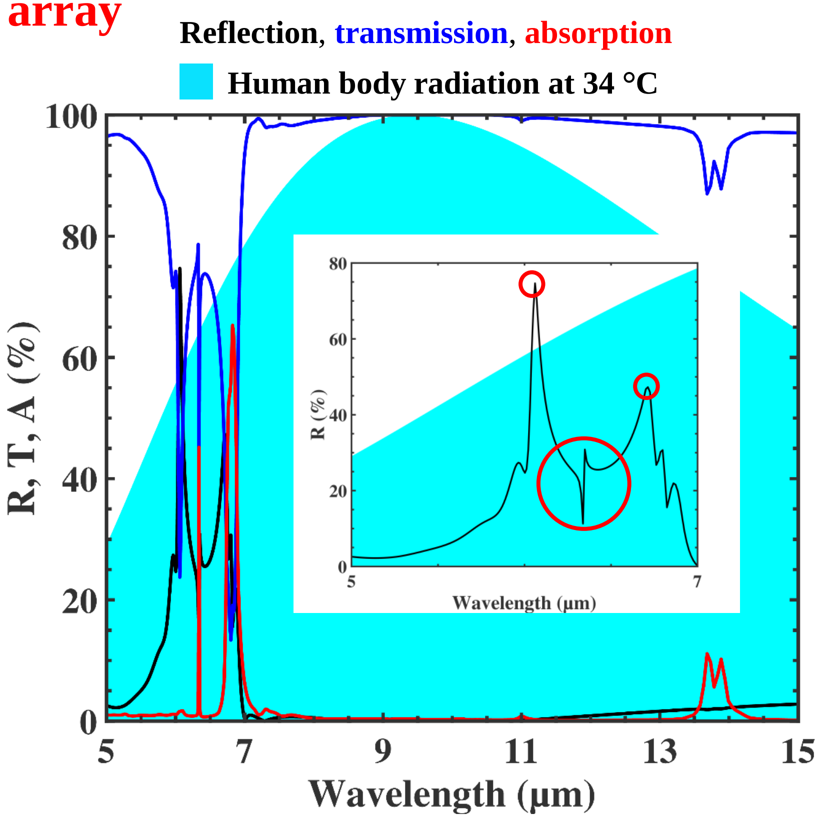
- **PE membrane drilled with triangular array**

h = 4 µm

D = 5.5 µm

P = 7 µm





Appearance of reflection peaks between 5 and 7 µm related to the structuration of the membrane

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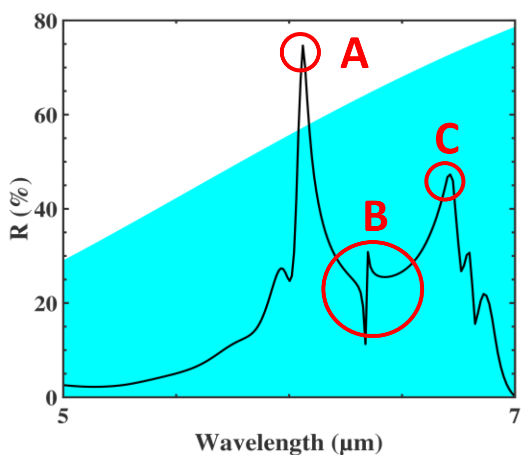
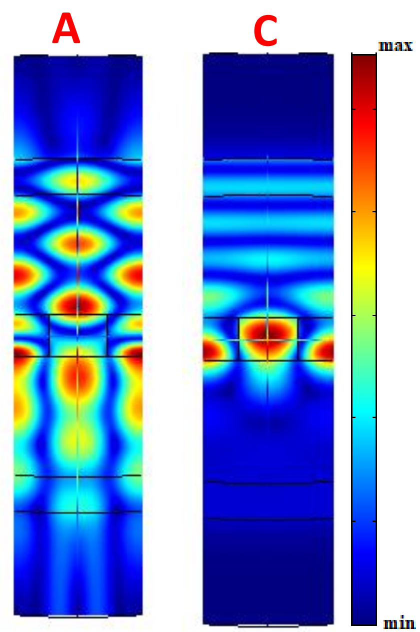
Origin of the peaks

Snapshots of the modulus of the electric field for the three peaks of reflection A, B and C.

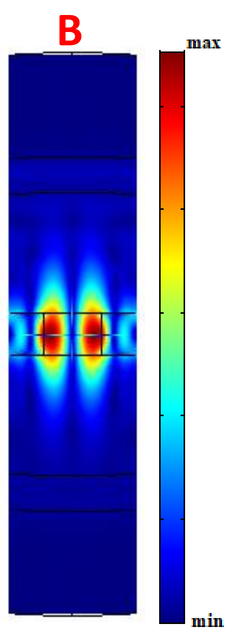


Antisymmetric modes with respect to the mid-plane of the membrane



Guided modes inside the membrane

Symmetric mode with respect to the mid-plane of the membrane



Mode confined in the air hole

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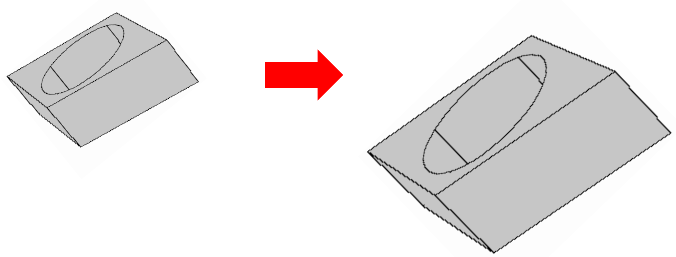
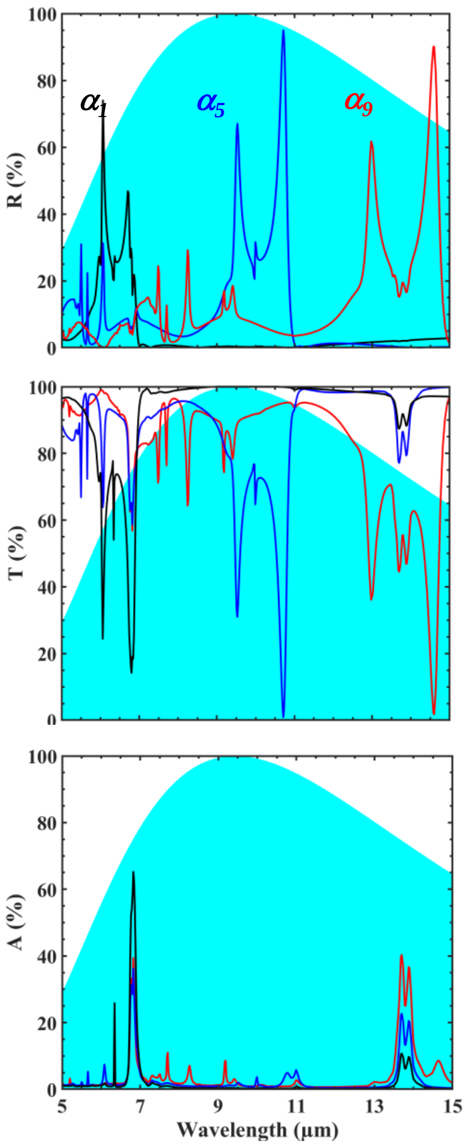
Effect of geometry

Variation of **h**, **D**, **P** according to a scaling factor $\boldsymbol{\alpha}$



Scaling factor α_i	Period P (µm)	Diameter D (µm)	Thickness h (µm)
α_1 = 1.0	7.0	5.5	4.0
α_3 = 1.28	9	7.1	5.1
α_5 =1.56	11.0	8.6	6.3
α_7 =1.84	13	10.2	7.4
α_9 = 2.12	15.0	11.8	8.6



Increasing the size of the geometrical parameters leads to the shift of the three reflective features A, B and C, towards higher wavelengths

Assaf S., Boutghatin M. et al, Scientific reports,2020

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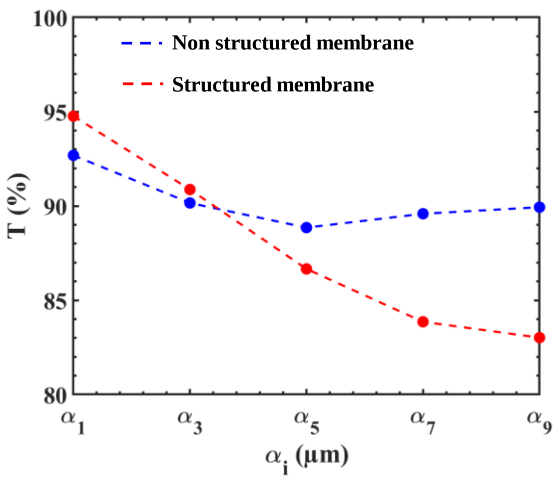
Efficiency coefficient associated to R, T and A

$$\eta = \frac{\int_{\lambda_{\min}}^{\lambda_{\max}} E_\lambda . \chi_\lambda . d\lambda}{\int_{\lambda_{\min}}^{\lambda_{\max}} E_\lambda . d\lambda}$$ where:

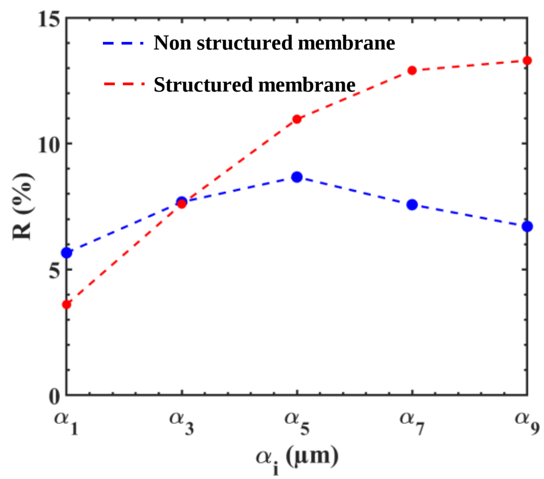
- χ_λ is R, T or A in the range $[\lambda_{min} - \lambda_{\max}]$ = [5-15 µm].
- E_λ is the human body radiation at $T_s = 34°C$.

Efficiency coefficient associated to T



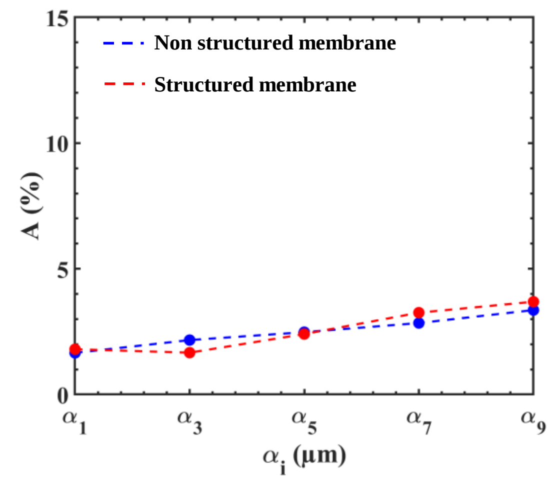
T decreases

Efficiency coefficient associated to R



R increases

Efficiency coefficient associated to A



A is almost constant

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Thermal balance

Conclusions and futur work

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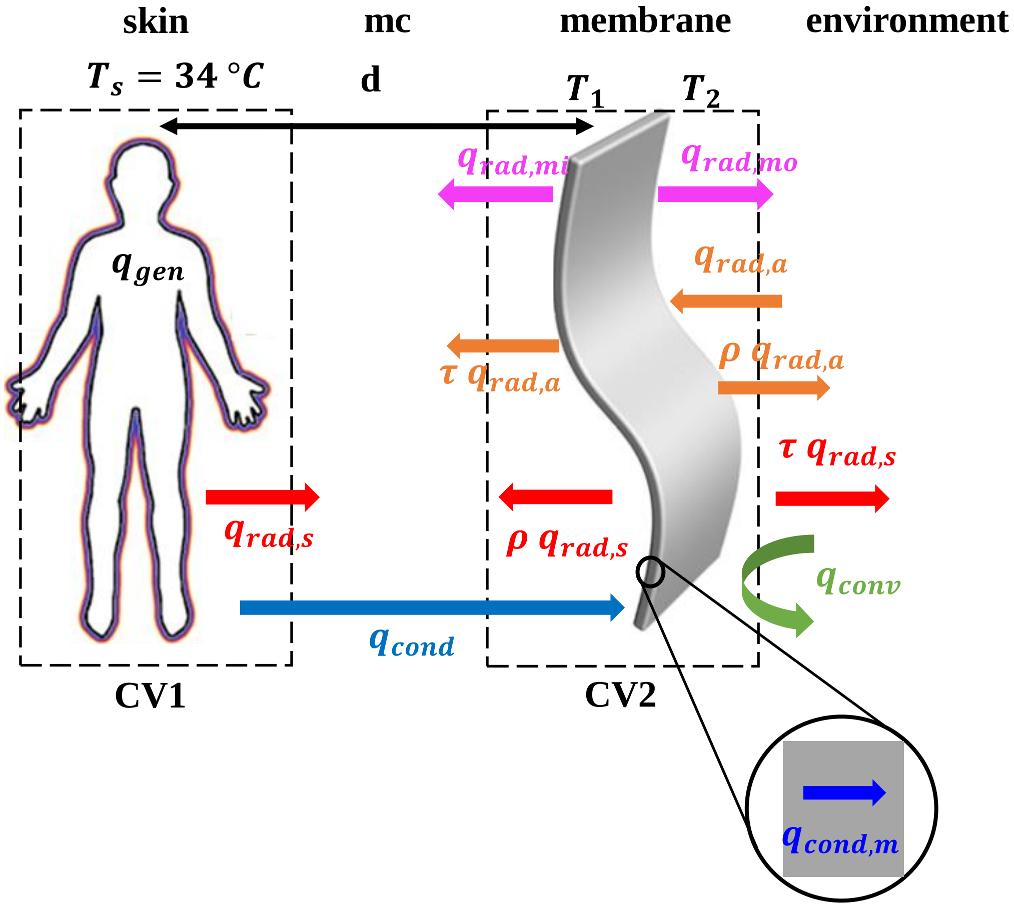
Heat transfer model



- **Conductive heat flux**

Fourier's law $$q_{cond} = k_{air}\frac{T_S - T_1}{d}$$

- **Convective heat flux**

Newton's law $$q_{conv} = h_c(T_2 - T_a)$$

- **Radiative heat flux**

Stephan-Boltzmann law

$$q_{rad,s} = \varepsilon_s \sigma T_S^4$$

$$q_{rad,a} = \varepsilon_a \sigma T_a^4$$

$$q_{rad,mi} = \varepsilon_m . \sigma T_1^4$$

$$q_{rad,mo} = \varepsilon_m . \sigma T_2^4$$

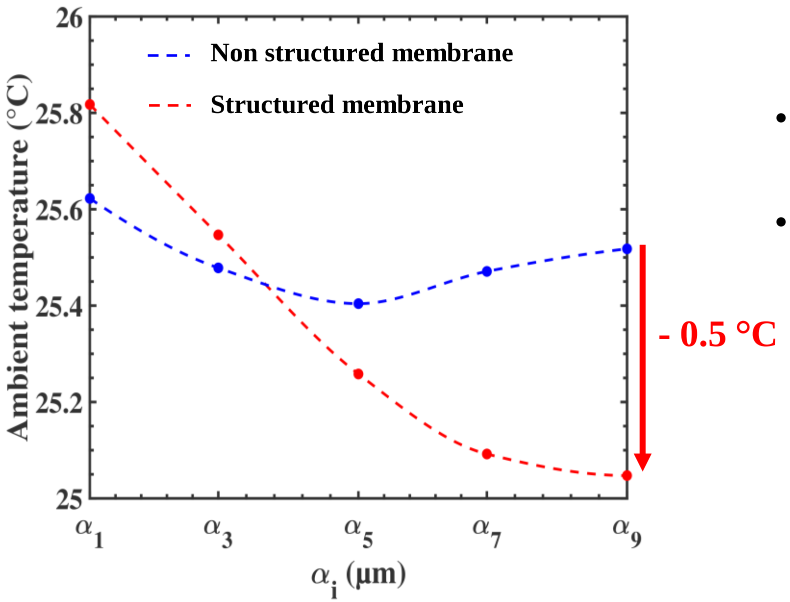
Assaf S., Boutghatin M. et al, Scientific reports,2020

Boutghatin M. et al, Nanomaterials,2020

ref article 20051

Thermal balance

Resolution of the thermal equations



- Due to very small thickness of our membrane, the temperature $T_1 = T_2$.
- For $\alpha_9 (P = 15\ \mu m, D = 11.8\ \mu m, h = 8.6\ \mu m)$, T_a = 25.5 °C when the skin is covered by a non structured membrane, however T_a = 25 °C when the same membrane is structured.

Room temperature (T_a) to achieve the thermal comfort ($T_s = 34°C$) as a function of geometrical parameters of non structured membrane and structured one.

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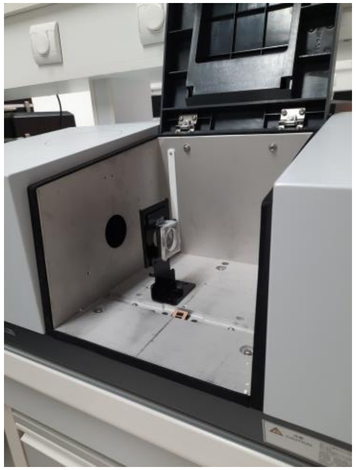
Conclusions

- The structuration parameters of a PE membrane can modulate the optical coefficient in the mid-infrared.
- To maintain the thermal comfort, the PE photonic crystal membrane acts as a modulator under thermal radiation emitted from the human body.
- Compared to a non structured PE membrane, the structured one maintains the thermal comfort with a lower ambient temperature of 0.5 °C.
- The presence of micro-holes enables air permeability and can promote water-wicking

Future work

Fabrication full PE membranes to compare the measured spectra with the simulation

Spin coating



FTIR

- Develop a technical method for structuring a PE membrane.
- We seek to study photonic membranes based on active polymer, sensitive to ambient temperature and humidity.

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Thank you for your attention