Polymer Photonic Crystal Membrane for Human Body Thermoregulation

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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

- Industry: 21%
- Transport: 32%
- Agriculture: 3%
- Buildings: 43%

Distribution of energy used in building

- Household appliances, lighting, TV: 16%
- Cooking: 7%
- Hot water: 12%
- CVC / HVAC: 65%

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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Mechanisms of heat transfer by the human body

Convection

Radiation

Evaporation

Distribution of the different mechanisms

Radiative transfers predominate


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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 wavelength 9.5 µm.

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Objective

What do we want?

- Maintain the thermal comfort ($T_s = 34 ^\circ C$) 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)

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)

Tong J.K. et al, ACS Photonics, 2015  
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 future work
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- Optical properties of polyethylene (PE) polymer
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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

Maxwell equation:

\[ \nabla \times (\varepsilon_r^{-1} \nabla \times H) = \left( \frac{\omega}{c} \right)^2 H \]

\[ \nabla \times (\nabla \times E) = \varepsilon_r \left( \frac{\omega}{c} \right)^2 E \]

FEM method by using commercial COMSOL software

PML: Perfectly Matched Layers
PBC: Periodic Boundary Condition

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Polymer membrane

- **Polyethylene (PE)**
  Thermostable polymer, used in a wide range of applications.
  It is textile compatible.
  Intrinsically transparent in the mid-infrared 5-15 µm.

\[
A = 100\% - R - T
\]

\[h = 4 \text{ µm}\]

Reflection, transmission, absorption

Human body radiation at 34 °C

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
  
  \[ h = 4 \, \mu m \]
  
  \[ D = 5.5 \, \mu m \]
  
  \[ P = 7 \, \mu m \]

\[ h = 4 \, \mu m \]

\[ D = 5.5 \, \mu m \]

\[ P = 7 \, \mu m \]

\[ A = 100\% - R - T \]

Appearance of reflection peaks between 5 and 7 \( \mu \)m 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

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

Guided modes inside 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 $\alpha$

<table>
<thead>
<tr>
<th>Scaling factor $\alpha_i$</th>
<th>Period $P$ (µm)</th>
<th>Diameter $D$ (µm)</th>
<th>Thickness $h$ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_1 = 1.0$</td>
<td>7.0</td>
<td>5.5</td>
<td>4.0</td>
</tr>
<tr>
<td>$\alpha_3 = 1.28$</td>
<td>9</td>
<td>7.1</td>
<td>5.1</td>
</tr>
<tr>
<td>$\alpha_5 = 1.56$</td>
<td>11.0</td>
<td>8.6</td>
<td>6.3</td>
</tr>
<tr>
<td>$\alpha_7 = 1.84$</td>
<td>13</td>
<td>10.2</td>
<td>7.4</td>
</tr>
<tr>
<td>$\alpha_9 = 2.12$</td>
<td>15.0</td>
<td>11.8</td>
<td>8.6</td>
</tr>
</tbody>
</table>

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

\[ \eta = \frac{\int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} E_{\lambda} \cdot \chi_{\lambda} \cdot d\lambda}{\int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} E_{\lambda} \cdot d\lambda} \]

where:

- \( \chi_{\lambda} \) is R, T or A in the range \([\lambda_{\text{min}} \text{–} \lambda_{\text{max}}] = [5\text{–}15 \mu\text{m}]\).
- \( E_{\lambda} \) is the human body radiation at \( T_{s} = 34^\circ\text{C} \).

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

Heat transfer model

- Conductive heat flux
  Fourier’s law  \( q_{\text{cond}} = k_{\text{air}} \frac{T_S - T_1}{d} \)

- Convective heat flux
  Newton’s law  \( q_{\text{conv}} = h_c (T_2 - T_a) \)

- Radiative heat flux
  Stephan-Boltzmann law
  \( q_{\text{rad},s} = \varepsilon_s \sigma T_S^4 \)
  \( q_{\text{rad},a} = \varepsilon_a \sigma T_a^4 \)
  \( q_{\text{rad},mi} = \varepsilon_m \sigma T_1^4 \)
  \( q_{\text{rad},mo} = \varepsilon_m \sigma T_2^4 \)

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

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Boutghatin M. et al, Nanomaterials, 2020
Thermal balance

Resolution of the thermal equations

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

Room temperature ($T_a$) to achieve the thermal comfort ($T_s = 34^\circ C$) 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

- 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.

Spin coating

FTIR

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Thank you for your attention