Effect of polydispersity on the transport and sound absorbing properties of three-dimension random fibrous media

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Sorrento SAPEM'23 常熟

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Agenda

1. **Introduction**
2. **Generation of fibrous media**
3. **Numerical calculations**
4. **Validation with measurements**
5. **Optimization**
6. **Conclusion and future works**

Introduction

❑ Context

Figure 1. Use of porous materials to reduce the noise in the automotive industry. Source: Adler Pelzer.

- Improving the sound experience inside the cabin
  - ✓ Increase acoustic comfort
  - ✓ Reduce noise pollution

- Use of acoustic materials as a passive solution
  - ✓ Granular
  - ✓ Foams
  - ✓ **Fibrous**.

❑ Materials: local heterogeneities with polydisperse fibers

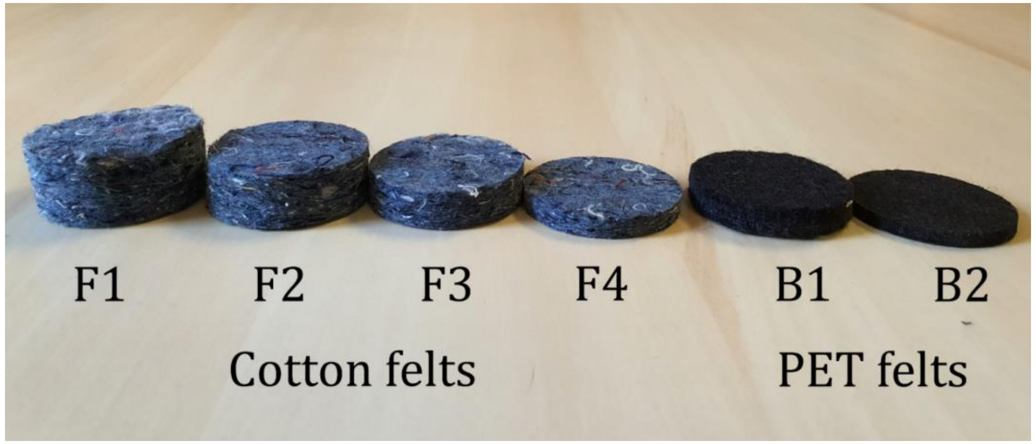


Figure 2. Thermo-compressed felts : a) Cotton felt, recycled fibers bonded from CoPET fibers; b) Felts made from recycled PET fibers.

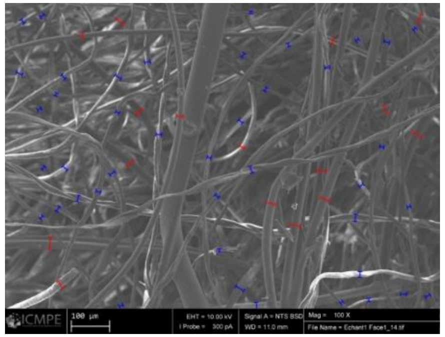
❑ Objectives:

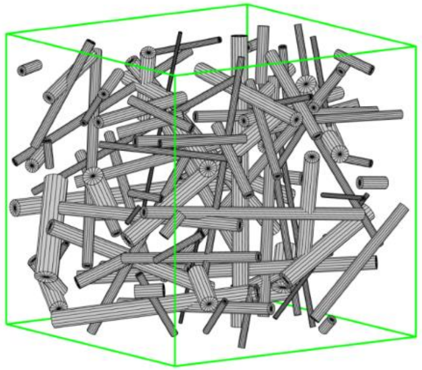
- ✓ Determine micro-macro links between microstructures of non-woven fibrous materials and their acoustical macro-behavior
- ✓ Identify optimal microstructures of the felts reaching the desired quantities, compatible with the corresponding manufacturing process parameters

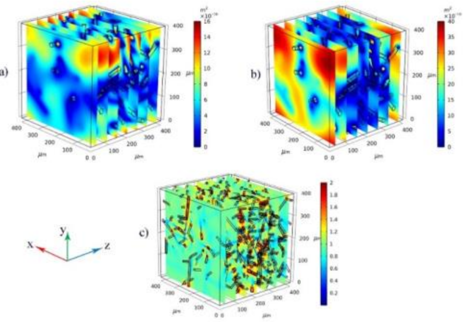
Introduction

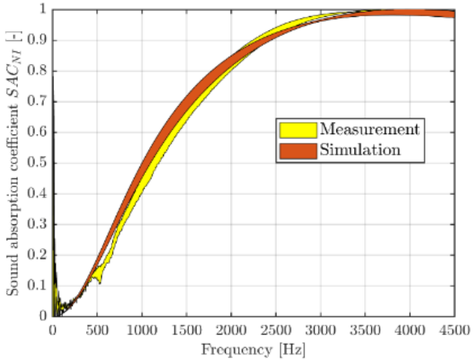
❑ Method: Hybrid multi-scale method combining finite element numerical simulation with semi-phenomenological models

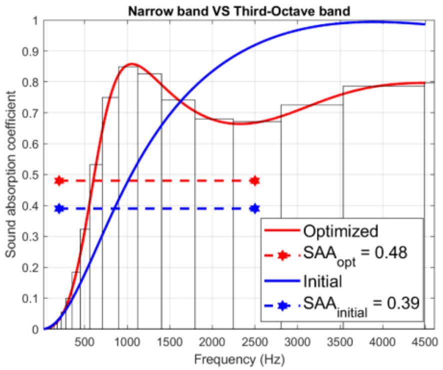
1. Identification of the morphological characteristics of the microstructures of the fibrous material
2. Generation of Representative elementary volumes (REVs) of random fibrous media from the microstructure acquisition
3. Numerical calculations
   - Determination of transport parameters (finite element model)
   - Estimation of acoustic properties (semi-phenomenological model)
4. Validation by experimental measurements
5. Optimization











Microstructure → Reconstruction → Numerical calculations → Validation → Optimization

Generation of fibrous media

❑ Microstructure analysis

- **Fiber diameter and orientation distributions**

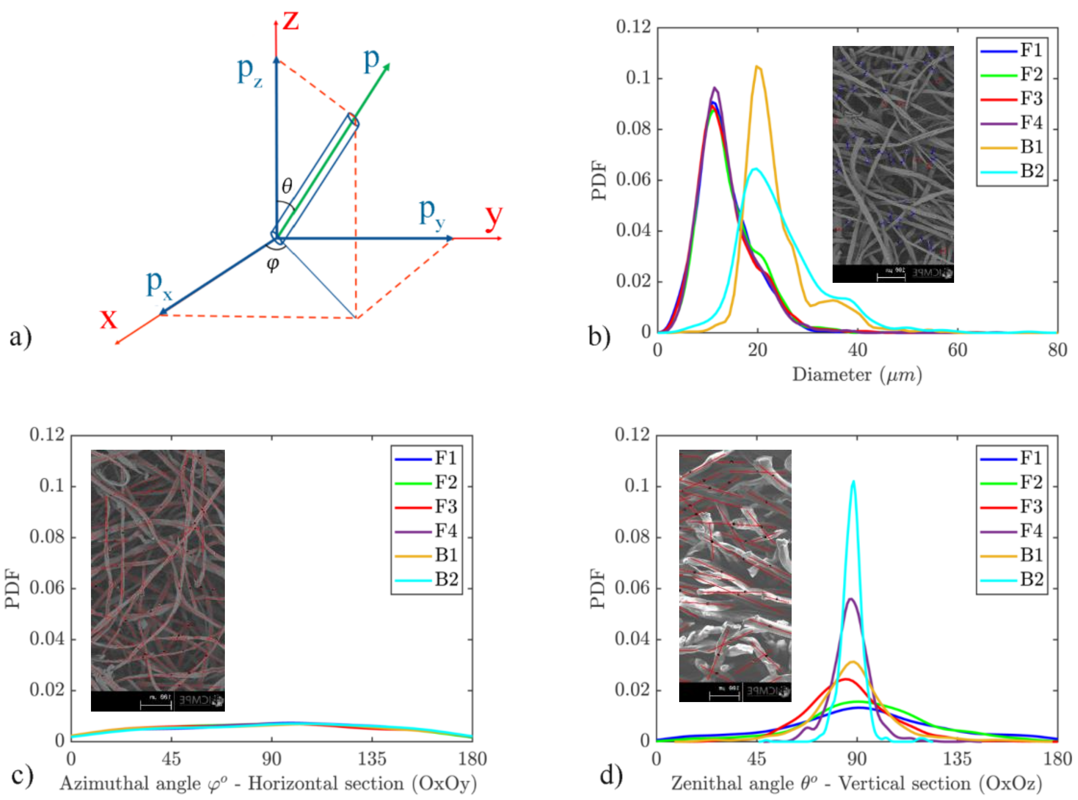


Figure 3. (a) The orientation of a fiber in spherical coordinate. The estimated probability density function of (b) the fiber diameter; (c) the azimuthal angle φ ; (d) the zenithal angle θ as plotted using a non-parametric kernel method.

❑ Reconstruction

- **Estimated microstructural descriptors**

Samples	ϕ	D_m (μm)	CV (%)	β
F1	0.948±0.005	13.5±5.6	40.3	1.4

Table 1. Measurements obtained by SEM images and estimated microstructural descriptors (known porosity).

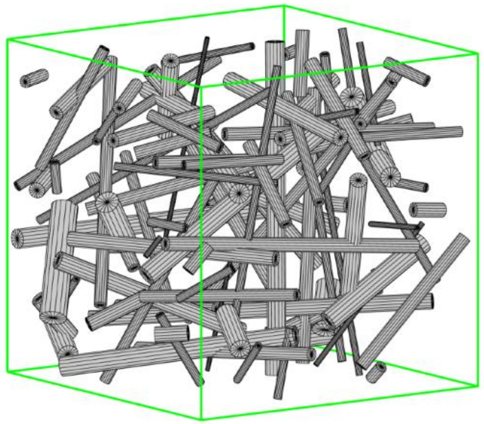


Figure 4. Polydisperse fibrous medium: Randomly overlapping fiber periodic structure of cotton felt F1.

Generation of fibrous media

Reconstruction

- **Orientation parameter:** Orientation distribution given here by the density function $p_\beta(\theta,\varphi) = \frac{1}{4\pi}\frac{\beta\sin\theta}{(1+(\beta^2-1)\cos^2\theta)^{\frac{3}{2}}}$

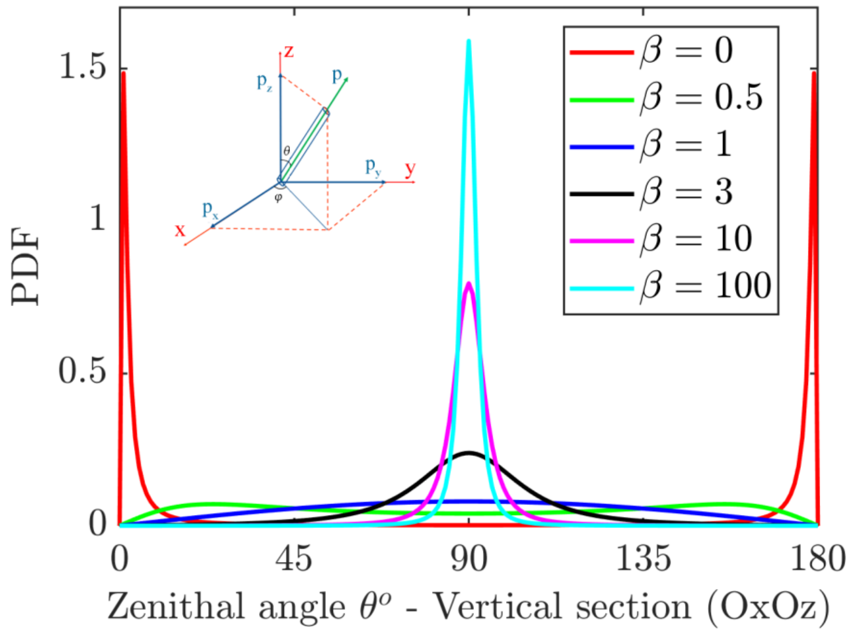


Figure 5. Various examples of the probability density function displaying the zenithal angle θ for different values of β.

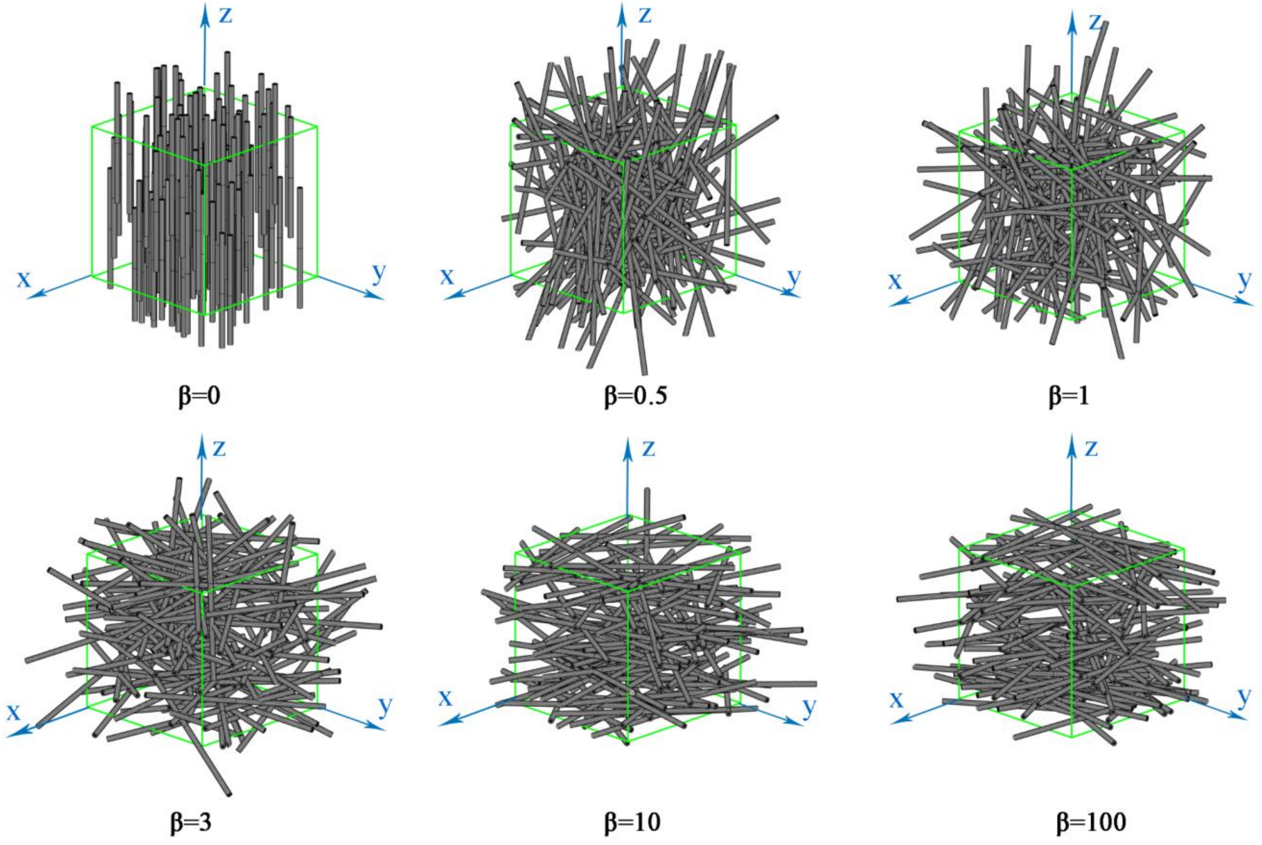


Figure 6. Various configurations corresponding to the variation of fiber orientation states with β ranging from 0 to 100, respectively.

Generation of fibrous media

Reconstruction

- **Fiber diameter**

- Gamma distribution: $f(D_i;\kappa,\theta)=\frac{D_i^{\kappa-1}e^{-\frac{D_i}{\theta}}}{\theta^{\kappa}\Gamma(\kappa)}$
- Average diameter: $D_m=\frac{\sum D_i}{N}=\kappa\theta$
- Coefficient of variation: $CV=\frac{\sigma_d}{D_m}$

  ✓ κ: shape parameter
  ✓ θ: scale parameter
  ✓ σ_d: standard deviation

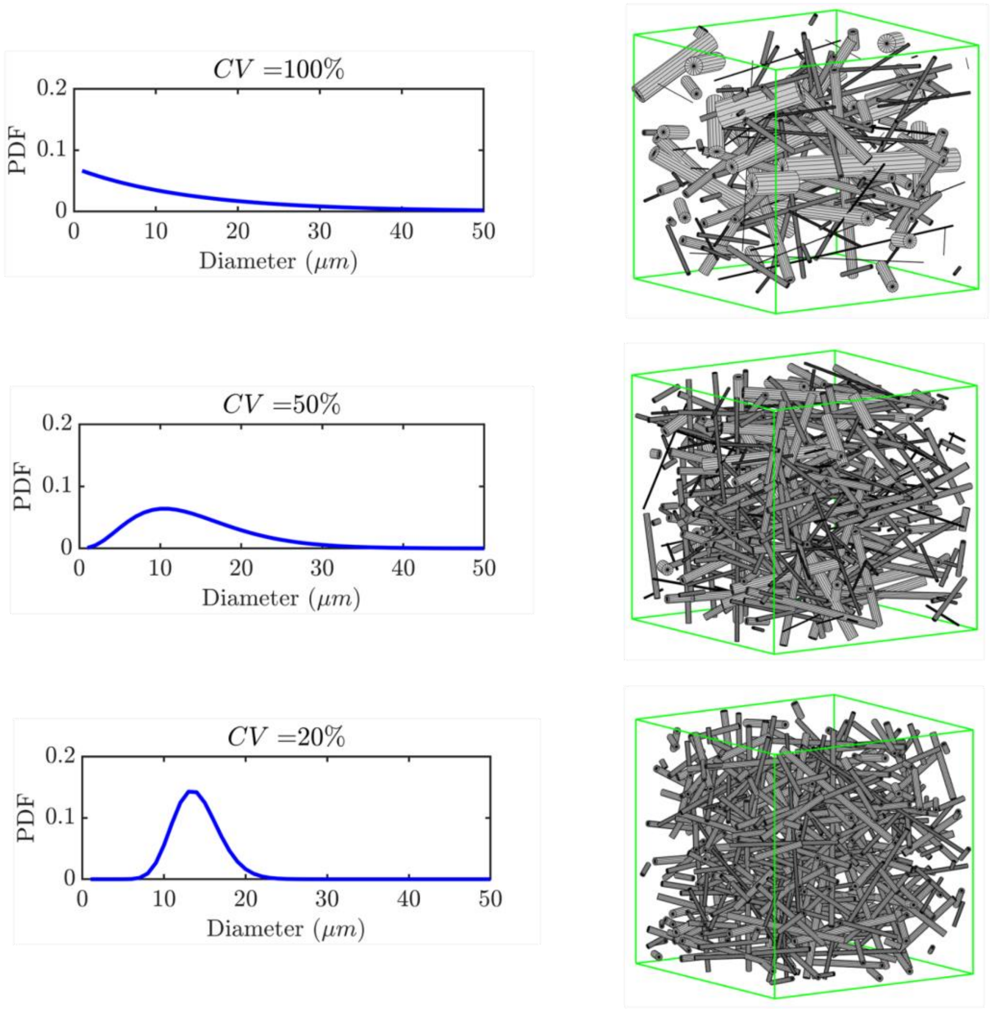
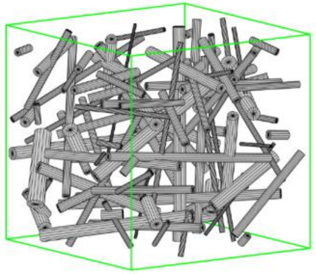


Figure 7. Illustration of various probability distribution functions of the fiber diameters (left) and geometrical configuration (right) corresponding to a variation of CV with a constant mean diameter and a constant porosity ($D_m = 13.5\ \mu m; \phi = 0.948$).

Numerical calculations

Samples	$D_m(\mu m)$	$D_v(\mu m)$	$D_{iv}(\mu m)$
F1	13.5±5.6	19.5±0.3	8.9±0.4

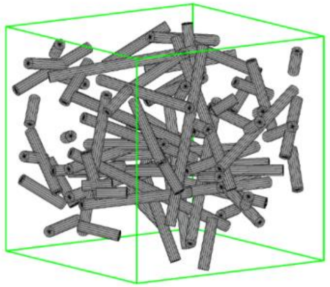
Mean diameter, volume weighted, and inverse volume weighted mean diameters.

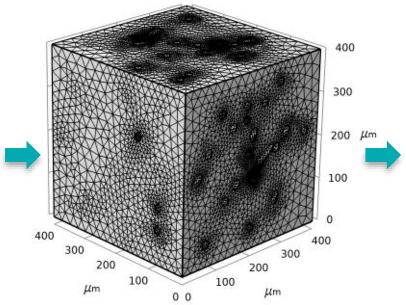


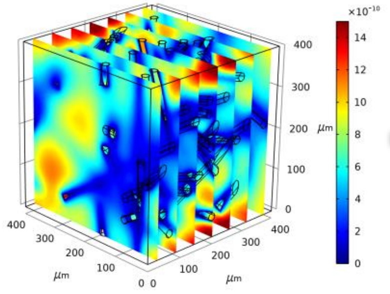
Polydisperse fibrous medium

- **Identification of REVs**
- **Numerical calculations (homogenization)**

$$D_v = \frac{\sum D_i V_i}{\sum V_i}$$

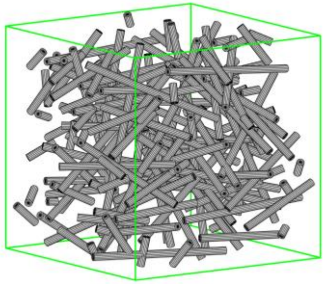




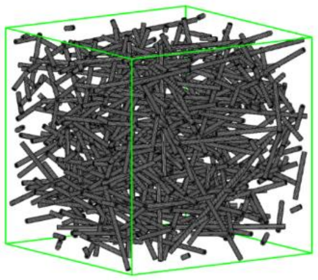


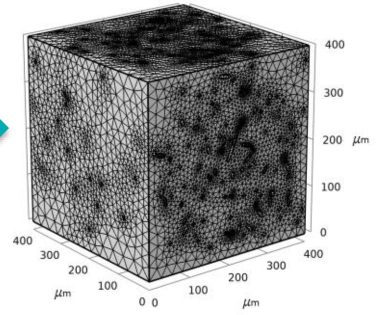
Low frequency transport parameters (k_0, k_0')

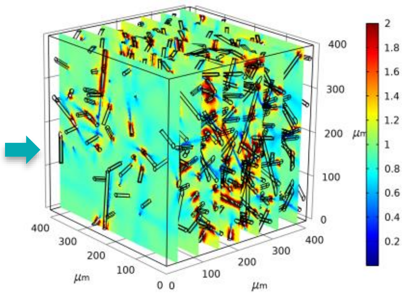
$$D_m = \frac{\sum D_i}{N_f}$$



$$D_{iv} = \frac{\sum D_i/V_i}{\sum 1/V_i}$$







High frequency transport parameters $(\alpha_\infty, \Lambda, \Lambda')$

Parametric study

Input data:

- Porosity ϕ
- Distributions of fiber diameters $\Gamma(D_m, CV)$
- Distributions of angular orientations of fibers $\beta(\theta, \varphi), \Omega_{zz}$

Weighted diameters (radii)

- Volume weighted radii r_v
- Inverse volume weighted radii r_{iv}

Numerical simulation with the corresponding REVs:

- $0.65 \le \phi \le 0.99$
- $0 \le \beta \le 20$ $(0 < \Omega_{zz} < 1)$

(Note that Ω_{zz} represents an alternative form of β normalized between 0 and 1)

Semi-analytical model

Analytical expressions

Outputs

- Transport parameters $k_0, k_0', \alpha_\infty, \Lambda, \Lambda'$
- Sound absorption coefficient at normal incidence (SAC_{NI})

- Viscous permeability k_0

$$log_{10}\left(\frac{k_0}{r_v^2}\right) = 0.7501\, log_{10}\left(\frac{\phi^3}{(1-\phi+0.0038)^2}\right) + 0.1313\Omega_{zz}^2 + 0.176\Omega_{zz} - 1.13$$

- Thermal permeability k'_0

$$\frac{k'_0}{r_v^2} = 0.08\frac{\phi^3}{(1-\phi+0.017)^2}$$

- Tortuosity α_∞

$$\alpha_\infty = \left(\frac{1}{\phi}\right)^{(-0.0914\Omega_{zz}^2 - 0.341\Omega_{zz} + 0.495)}$$

- Thermal characteristic length Λ'

$$\frac{\Lambda'}{r_{iv}} = 0.977\frac{\phi}{1-\phi+0.00044}$$

- Viscous characteristic length Λ

$$\frac{\Lambda'}{\Lambda} = 1 + (-0.1578\Omega_{zz}^2 - 0.666\Omega_{zz} + 0.9254)$$

- Weighted radius r_v, r_{iv}

$$\frac{r_v}{r_m} = (0.0002\, CV^2 - 0.00014CV + 1.003)$$

$$\frac{r_{iv}}{r_m} = 0.9085e^{-\left(\frac{CV-4.742}{31.97}\right)^2} + 0.4168e^{-\left(\frac{CV-42.37}{25.92}\right)^2}$$

Validation

Transport parameters

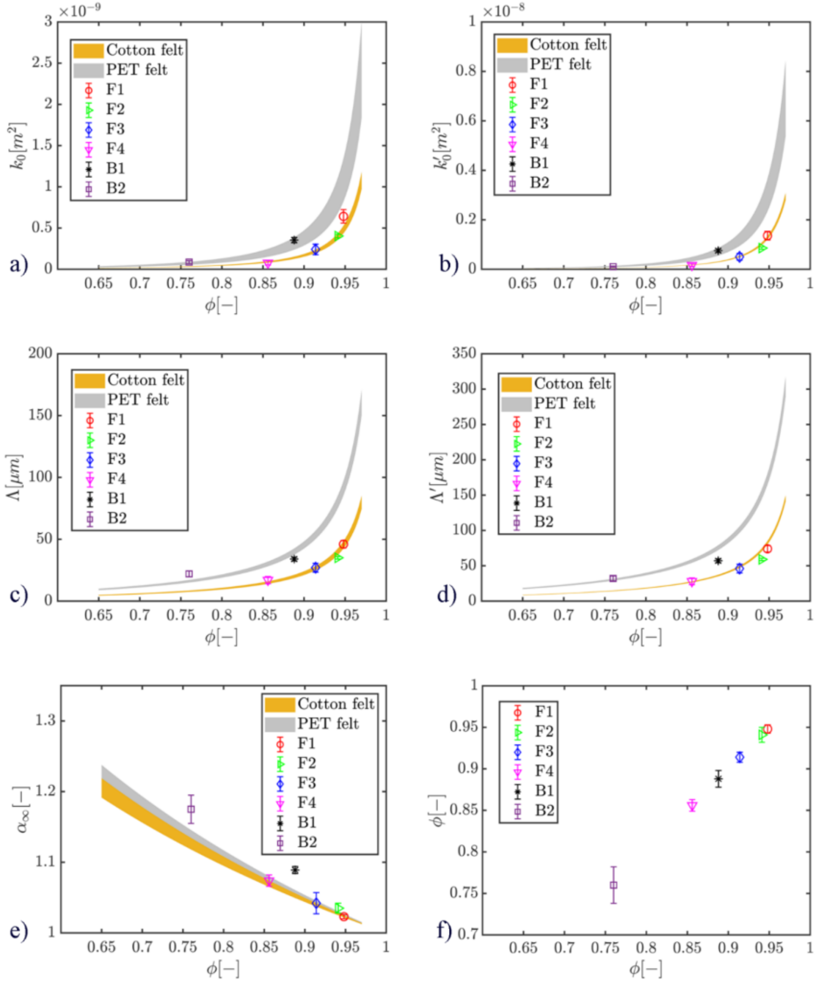


Figure 8. Comparison of the transport parameters between the predictions of the semi-analytical model and the experiments

Sound absorption coefficient

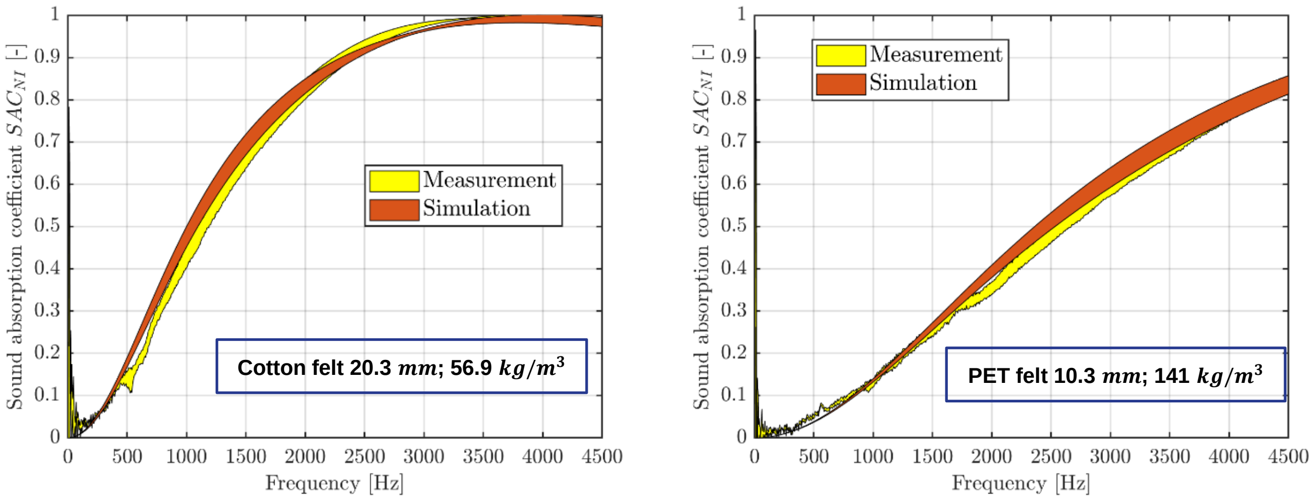


Figure 9. Comparison of the sound absorption coefficient at normal incidence (SAC_{NI}) between the predictions of the numerical simulations and the measurement.

The simulated values are in good agreement with the experimental data (without adjusted parameter, using only the microstructural data as inputs of the model).

Optimization

❑ Transport parameters

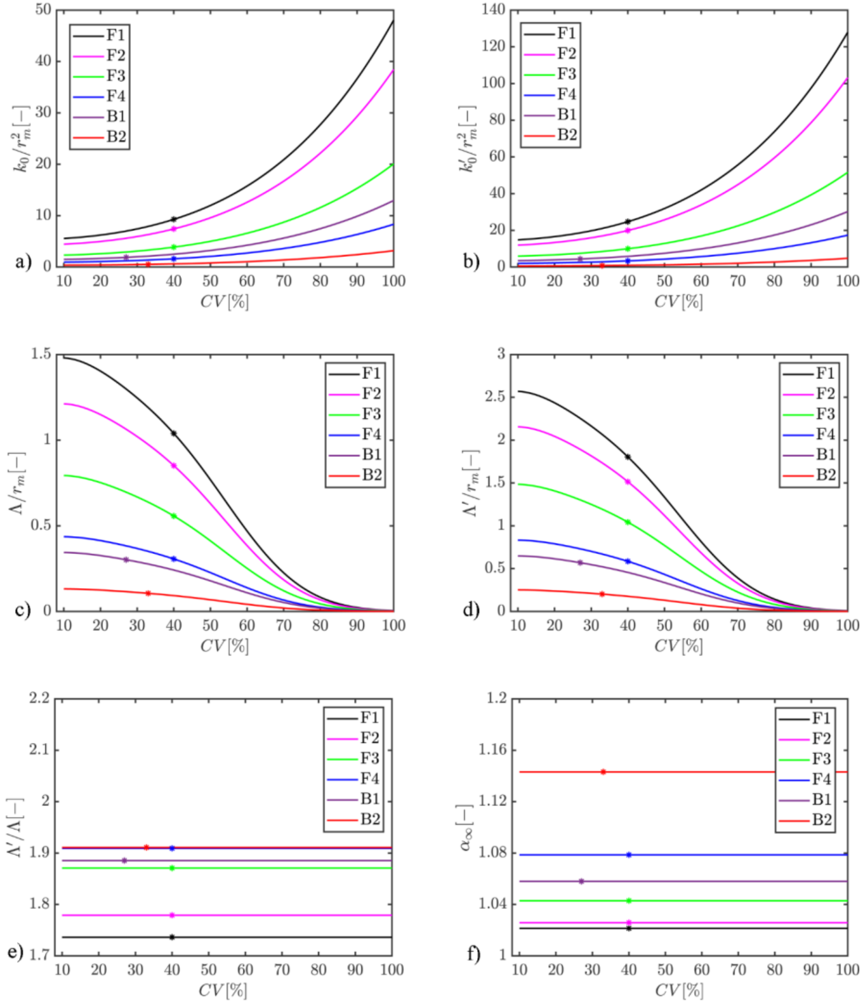


Figure 10. Evolution of transport parameters following the coefficient of variation.

❑ Sound absorption coefficient

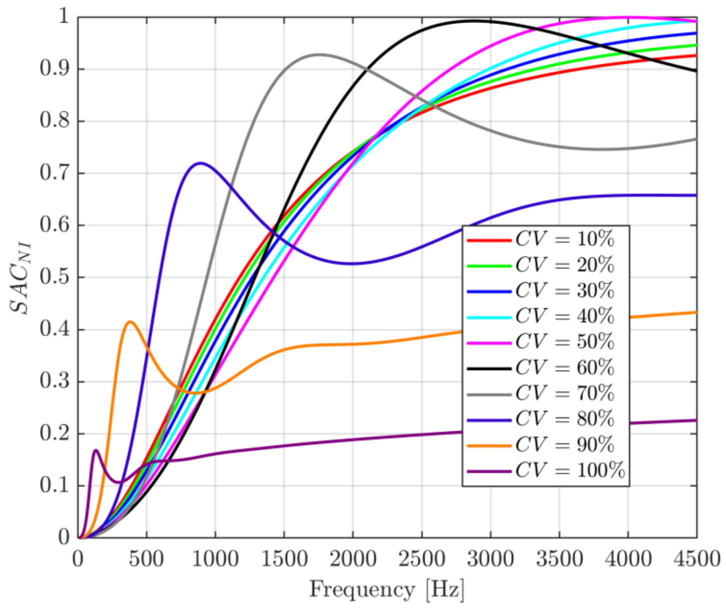


Figure 11. Evolution of sound absorption coefficient at normal incidence (SAC_{NI}) following the coefficient of variation.

Coefficient of variation **CV** - a new optimization lever of sound absorbing fibrous materials.

Optimization

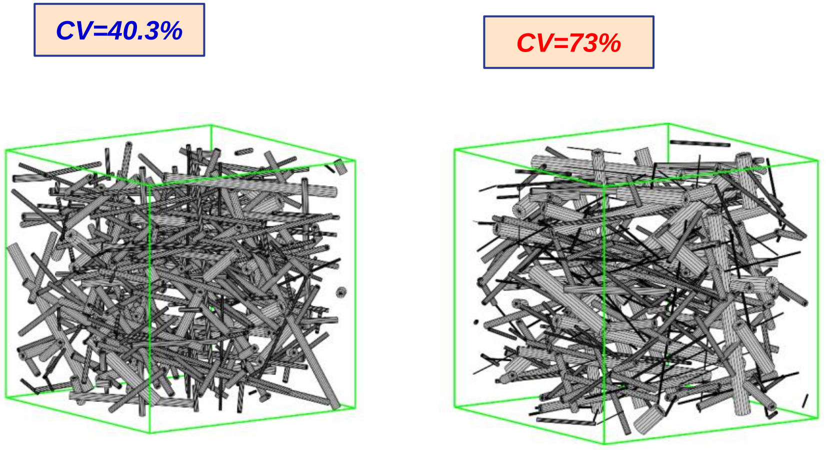
- *Fixed parameters* = $\{L_s, \phi, R_m, \beta\}$
  - ✓ L_s: thickness
  - ✓ ϕ: porosity
  - ✓ R_m: mean radii
  - ✓ β: *orientation*
- *Optimized variables (coefficient of variation)*
  - ✓ $10 \leq CV \leq 300$

- *Cost function:* SAA *- is the sound average absorption coefficients for a material across 16 third octave bands* f_i *ranging from 125 to 4500 Hz:*

$$SAA = \frac{1}{16} \sum_{f_i=125}^{4500} SAC_{NI}(f_i)$$

The optimization was based on a differential evolution (DE) algorithm.

Cotton felt F1



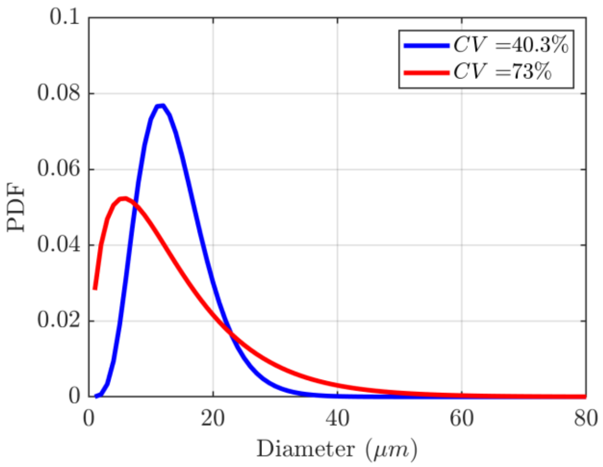


Figure 12. Comparison of the Gamma distribution of fiber diameters obtained through SEM images, cotton felt F1 and the Gamma distribution of fiber diameters after optimization.

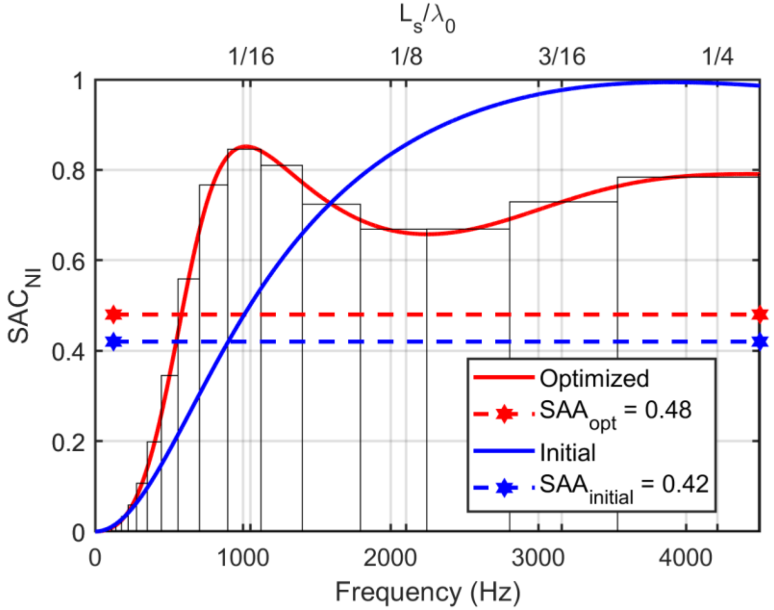


Figure 13. Initial and optimal sound absorption coefficients of cotton felt F1.

Conclusion and Future works

Conclusion

- Micro-macro relationships between the parameters describing the local geometry of non-woven fibrous materials and their acoustical macro behavior were determined.
- Local geometry parameters of the model:
  - the open porosity $\boldsymbol{\phi}$,
  - the distributions of fiber diameters parameterized by a gamma law $\boldsymbol{\Gamma}(\boldsymbol{shape}, \boldsymbol{scale}) \equiv \boldsymbol{\Gamma}(\boldsymbol{D_m}, \boldsymbol{CV})$
  - the angular orientations $\boldsymbol{\beta}(\boldsymbol{\theta}, \boldsymbol{\varphi})$
- The model enables optimization of the non-wovens, example is proposed to illustrate the possible gains in sound absorption using the polydispersity of fiber diameters as a new lever of optimization.

Future works

- Experimental validation of an optimized configuration
- Elaboration of a tri- modal model as an improvement of the developed model (for a closer link with the manufacturing process)
- Extension to elastic properties: would enable an overall optimization strategy including both the SAC and the transmission loss

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Thanks for watching!

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