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A Hybrid Acoustic Model for Composite Materials Composed of Fibers and High Surface Area Particles

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A Hybrid Acoustic Model for Composite Materials Composed of Fibers and High Surface Area Particles

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Content

- Review of the rigid model
- The hybrid model for composites
- The measurement and parameter fitting
- Conclusions

What are high surface area particles?

Activated carbon

Silica gel

Zeolite

Surface area

$> 1000 \text{ m}^2/\text{g}$

$> 500 \text{ m}^2/\text{g}$

$> 400 \text{ m}^2/\text{g}$

The porosity exists in different levels, and thus, is defined in a hierarchical way.

The existence of the pores inside the particles makes the surface area of this type of materials larger compared with solid particles.

Review of the rigid model for particle stacks

A typical high surface area material is activated carbon, for which a triple porosity model was proposed by Venegas and Umnova in 2016

The sorption process is correlated with an improvement of low frequency acoustic absorption, as it softens the equivalent fluid.

Need a fibrous matrix to hold these high surface area particles -> Particle-fiber composites

Or it can be explained by the increased wave-number/reduced phase speed resulting from decreased stiffness

Review of the rigid model for particle stacks

A rigid model for materials with two levels of porosity was proposed by Venegas and Boutin in 2017.

Molecules adsorbed on pore wall
Molecules moving through pore

The transport void fraction can be calculated as,
 $\phi = 1 - d/r_m$

Two diffusion mechanisms applied in micropores in parallel

Interstitial space

- The porosities are defined at two levels, i.e., the interstitial space between particles is defined as the macroscopic pores, while those within particles are defined as micropores. The corresponding porosities are denoted as ϕ_p and ϕ_m .
- The advantage of such definition is that the microporosity is a constant property for the same type of materials no matter how the particles are arranged.

With the illustration above,

$$\phi_p = \frac{\text{Blue area}}{\text{Hexagon area}}$$

$$\phi_m = \frac{\text{White dots area}}{\text{Black circles area}}$$

Review of the rigid model for particle stacks

Interstitial space

For spherical particles, the bulk modulus of the interstitial fluid can be calculated with corresponding thermal permeability k'_p ,

$$B_p = \frac{\gamma P_0}{\phi_p} \left(\gamma - j\omega\rho_0 Pr(\gamma - 1) \frac{k'_p}{\phi_p \eta} \right)^{-1}$$

While the sorption and diffusion in micropores are accounted for by,

$$B_m = \frac{\gamma P_0}{\phi_p} \left(\gamma M_h \left(1 - \frac{j\omega G(\omega)}{(1 - \phi_p) \mathcal{D}_{app}} \right) \right)^{-1}$$

The total bulk modulus,

$$B = (1/B_p + 1/B_m)^{-1}$$

For the rigid model, the wavenumber in the porous material, q , is related to the viscous permeability k_{tb} and the bulk modulus B ,

$$q = \omega \sqrt{\eta / j\omega k_{tb} B}$$

With the wavenumber obtained, the absorption coefficient can be further calculated as,

$$\alpha = 1 - \left| \frac{z_n - 1}{z_n + 1} \right|^2$$

where z_n is the normalized surface impedance,

$$z_n = -j \frac{\rho_{eq} \omega}{q \rho_0 c_0} \cot(qd)$$

The hybrid model for composites

Flow resistivity from particle is far less than that from fibers

$$\sigma \approx \sigma_f$$

Apply JCA model and the relation between flow resistivity and characteristic lengths

$$\Lambda = \sqrt{\frac{8\eta\alpha_\infty}{\phi\sigma}}$$

$$\Lambda' = 2\Lambda$$

Takes the diffusion and sorption associated with micropores into consideration

Use Tarnow's equation to obtained flow resistivity σ

$$\sigma = \frac{4\pi\eta s_f}{\pi r_f^2 (-0.64 \ln s_f + s_f - 0.737)}$$

Interstitial space filled with equivalent fluid described by JCA model

Apply double porosity model

The hybrid model for composites

Measurement and optimization

The measurement results include absorption coefficient of **zeolite** particles and **silica gel** particles, and fiber-based composites made with ground zeolite particles, and silica gel particles.

The measurements were conducted in a vertically positioned standing wave tube, following standard E1050 for two microphone standing wave tube tests.

The measured absorption coefficients are then compared with model prediction for parameter fitting.

$$\begin{aligned} \min_{\mathbf{x}} \quad & f(\mathbf{x}) = \mathbf{w}^T (\boldsymbol{\alpha} - \boldsymbol{\alpha}_m)^2 / N \\ \text{s. t.} \quad & \mathbf{x}_{lb} < \mathbf{x} < \mathbf{x}_{ub} \end{aligned}$$

The optimization procedure is based on **particle swarm optimization**, which is realized by the constrained particle swarm optimization package.

During the fitting, the measurements below 100 Hz were discarded.

Results – Zeolite particle stack

ground zeolite particles
500 μm

ground zeolite particles
10.0 μm

For validation of the rigid model, a 30-mm-thick stack of zeolite particles, which were **not** ground, was tested.

The particle has a size of 2 mm, and pore size mode of 0.5 nm.

Input parameters	Fitted values
ϕ_p	0.30
ϕ_m	0.54
r_m [nm]	0.26
b [Pa ⁻¹]	1.0×10^{-6}
$\mathcal{D}_{app}$ [m ² /s]	4.0×10^{-10}

Results – Silica Gel particle stack

Silica gel particles

500 μm

Silica gel particles

10.0 μm

For validation of the rigid model, a 20-mm-thick stack of silica gel particles was tested. The particles had sizes ranging from 200 μm to 500 μm , and pore size mode of 6 nm.

Input parameters	Fitted values
ϕ_p	0.26
ϕ_m	0.60
r_p [mm]	0.22
r_m [nm]	3.5
b [Pa^{-1}]	2.3×10^{-6}
$\mathcal{D}_{app}$ [m^2/s]	1.4×10^{-5}

Results – Particle Stacks

A possible explanation for the difference behavior of the stacks is the different particle sizes.

Closer results with micro-pores open and closed for zeolite particles compared with silica gel particles. It is directly from the difference in fitted diffusivity, which is further related to the pore size.

The Fitting result shows that the rigid model of double porosity material can provide predictions that match well the measurements for both cases. Thus, the rigid model is validated and can then be used in the hybrid model.

Results – Silica Gel/Fiber composite

A cut sample of silica gel – fiber composite. The sample had a basis weight of 423 GSM, with particles accounting for 30% of its weight. The measurement was taken with 3 layers of samples stacked together, with a total nominal thickness of 10 mm.

Input parameters	Fitted values	Input parameters	Fitted values
d [mm]	13	b [Pa ⁻¹]	7.1×10^{-6}
ϕ_m	0.59	$\mathcal{D}_{app}$ [m ² /s]	9.2×10^{-5}
r_p [mm]	0.14	r_f [μm]	3.2
r_m [nm]	2.3	α_∞	2.0

Results – Zeolite/Fiber composite

A cut sample of zeolite – fiber composite. The sample has a basis weight of 415 GSM, with particles accounting for 40% of its weight. The measurement was taken with 3 layers of samples stacked together, with a total nominal thickness of 10 mm. The ground zeolite particles had a particle size ranging from 210 μm to 450 μm .

Input parameters	Fitted values	Input parameters	Fitted values
d [mm]	12	b [Pa^{-1}]	7.7×10^{-6}
ϕ_m	0.56	$\mathcal{D}_{app}$ [m^2/s]	1.0×10^{-9}
r_p [mm]	0.105	r_f [μm]	2.7
r_m [nm]	0.22	α_∞	2.0

Conclusions

Summary

- The rigid model was validated for the particle stacks
The double porosity model provides prediction closely matching the measured absorption coefficients of particle stacks
- The micropores helped improve the absorption coefficient of the particle stacks
The difference in contribution of micropores comes from the difference in fitted diffusivity, which is further related to micropore dimensions
- The hybrid limp model is able to closely match the composite measurements
For the fiber-based composites with zeolite and silica gel particles, the model is able to generate predictions that match the measurement of absorption coefficients well

Future work

- Study composites with higher concentration of particles
- Developing a poro-elastic version of the hybrid model to take the elasticity of the frame into consideration
- The high surface area particles made from different materials, and with different sizes of pores will be studied

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Thank you !

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