Sorrento SAPEM'23 常熟

Towards a control of acoustic energy conversion in structured porous materials

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Università degli Studi di Napoli Federico II

Laboratorio di Acustica del DII

Université Gustave Eiffel

Di Giulio, Perrot, Dragonetti

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- Energy conversion inside a porous material
- Thermoviscous behaviour
- Acoustic fields inside a porous material: pressure, velocity, temperature
- Geometry design to control viscous and thermal phenomena

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Energy conversion inside a porous material

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Geometry design to control viscous and thermal phenomena

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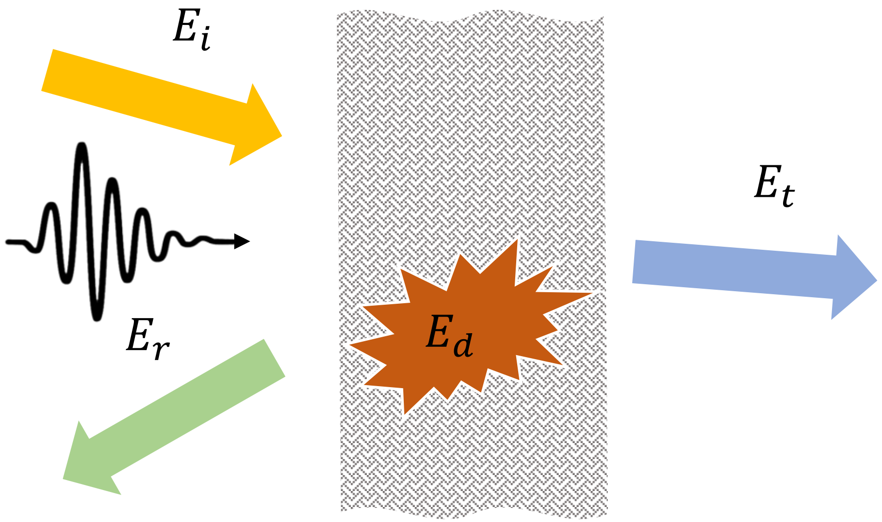
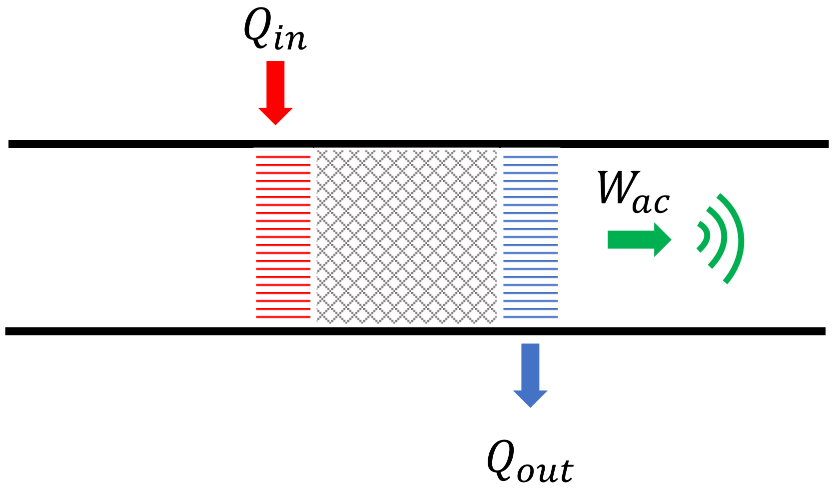
Porous materials applications

Sound absorption application



Thermoacoustic conversion



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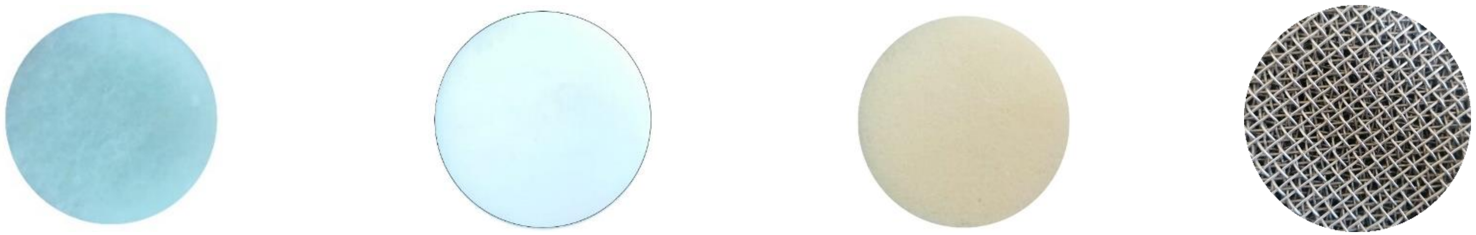
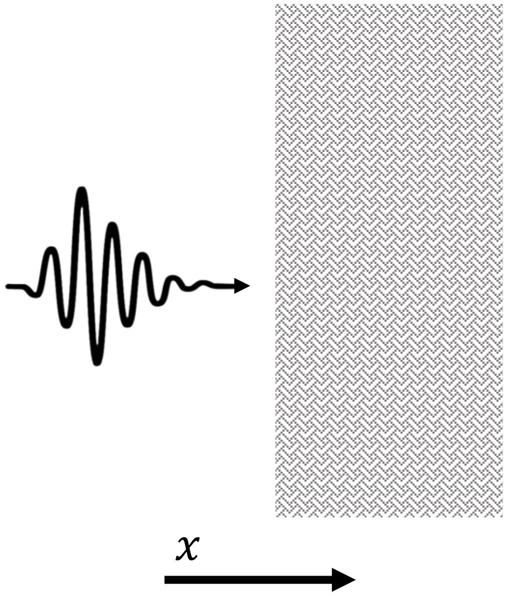
Energy conversion inside a porous material



$$\dot{E} = \frac{1}{2}\Re[\tilde{p}_1 U_1]$$



$$\frac{d\dot{E}}{dx} = \frac{1}{2}\Re\left[\tilde{U}_1 \frac{dp_1}{dx} + \tilde{p}_1 \frac{dU_1}{dx}\right]$$

$$\frac{d\dot{E}}{dx} = -\frac{1}{2} r_\nu |U_1|^2 - \frac{1}{2r_\kappa}|p_1|^2 + \Re[g\tilde{p}_1 U_1]$$

Swift, G. W. (1998). Thermoacoustic engines. *The Journal of the Acoustical Society of America*, *84*(4), 1145.

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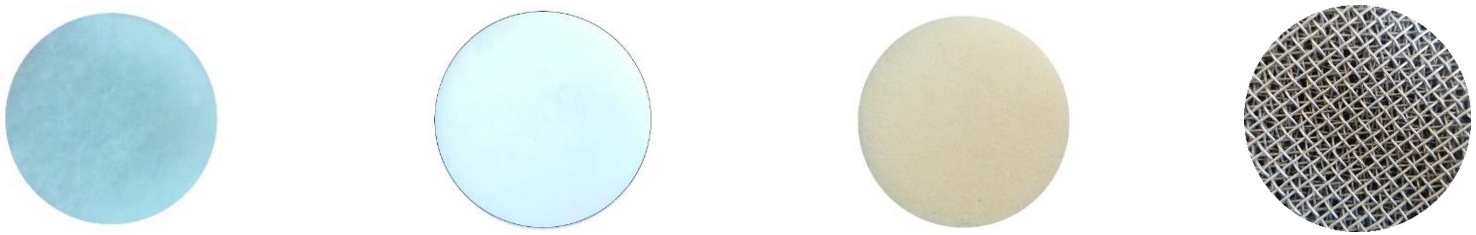
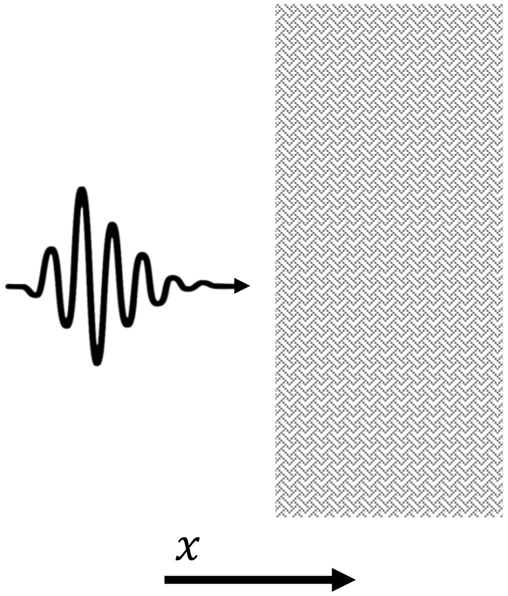
Energy conversion inside a porous material



Fluid properties and micro-geometrical features

$$r_\nu = \frac{\omega\rho_0}{A}\frac{\Im[-f_\nu]}{|1-f_\nu|^2}$$

Acoustic Volume Velocity field



$$\frac{d\dot{E}}{dx} = -\frac{1}{2}r_\nu|U_1|^2 - \frac{1}{2r_\kappa}|p_1|^2 + \Re[g\tilde{p}_1U_1]$$

Swift, G. W. (1998). Thermoacoustic engines. *The Journal of the Acoustical Society of America*, *84*(4), 1145.

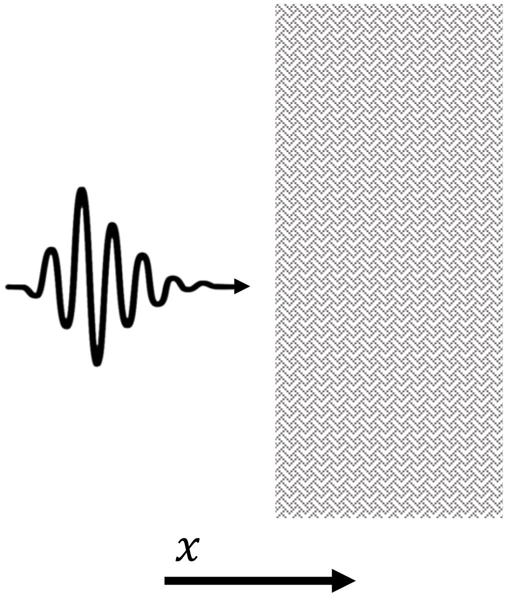
Energy conversion inside a porous material

Fluid properties and micro-geometrical features

$$\frac{1}{r_\kappa} = \omega A R \frac{\Im[-f_\kappa]}{|1-f_\kappa|^2}$$

$$\tau_1 = \frac{1}{\rho_0 c_p}(1-f_\kappa)p_1$$

Acoustic Temperature field



$$\frac{d\dot{E}}{dx} = -\frac{1}{2}r_\nu|U_1|^2 - \frac{1}{2r_\kappa}|\tau_1|^2 + \Re[g\tilde{p}_1 U_1]$$

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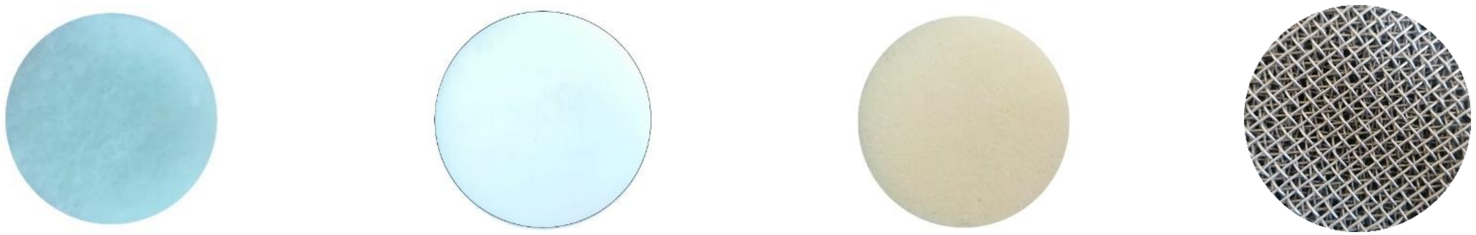
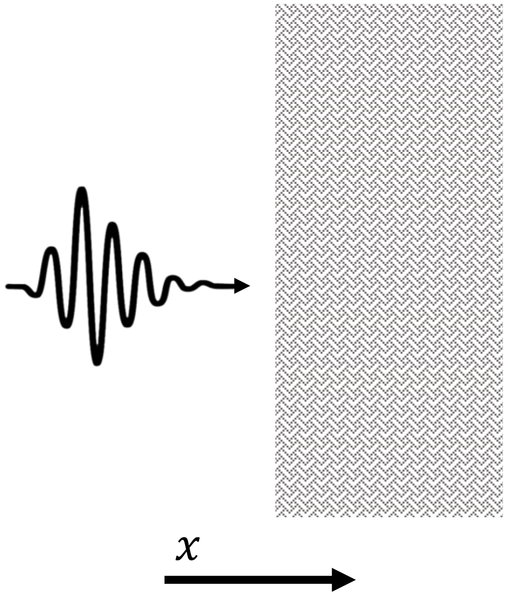
Energy conversion inside a porous material





Thermoacoustic gain

$$\boldsymbol{g} = \frac{(\boldsymbol{f}_{\kappa} - \boldsymbol{f}_{\nu})}{(\mathbf{1} - \boldsymbol{f}_{\nu})(\mathbf{1} - \boldsymbol{P}_{r})} \frac{\nabla T_m}{T_m}$$

$$\frac{d\dot{E}}{dx} = -\frac{1}{2} r_{\nu} |U_1|^2 - \frac{1}{2 r_{\kappa}} |\tau_1|^2 + \Re[\boldsymbol{g}\tilde{\boldsymbol{p}}_1 \boldsymbol{U}_1]$$

Swift, G. W. (1998). Thermoacoustic engines. *The Journal of the Acoustical Society of America*, *84*(4), 1145.

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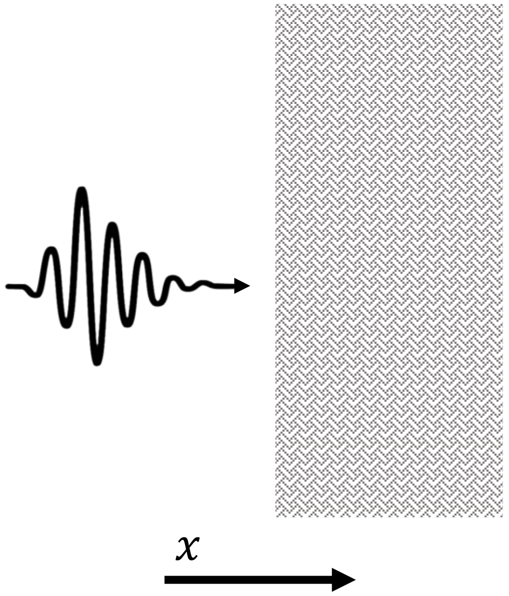
Energy conversion inside a porous material

$$\frac{d\dot{E}}{dx} = \frac{d\dot{E}_\nu}{dx} + \frac{d\dot{E}_\kappa}{dx} + \frac{d\dot{E}_{\text{gain}}}{dx}$$



$$\frac{d\dot{E}}{dx} = -\frac{1}{2} r_\nu |U_1|^2 - \frac{1}{2r_\kappa} |\tau_1|^2 + \Re[g\tilde{p}_1 U_1]$$

Swift, G. W. (1998). Thermoacoustic engines. *The Journal of the Acoustical Society of America*, *84*(4), 1145.

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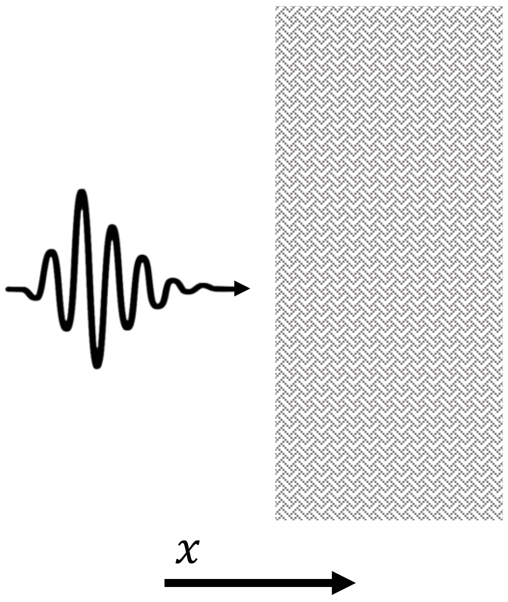
Thermoviscous behaviour



Viscous dissipation

$$\frac{d\dot{E}_\nu}{dx} = -\frac{1}{2}\frac{\omega\rho_0}{A}\frac{\Im[-f_\nu]}{|1-f_\nu|^2}|U_1|^2$$

$$\dot{E}_{\nu,\mathrm{tot}} = \int_L -\frac{1}{2}\frac{\omega\rho_0}{A}\frac{\Im[-f_\nu]}{|1-f_\nu|^2}|U_1|^2\,dx$$

$$\dot{E}_{\nu,\mathrm{tot}} = -\frac{1}{2}r_\nu\int_L |U_1|^2\,dx$$

Thermal dissipation

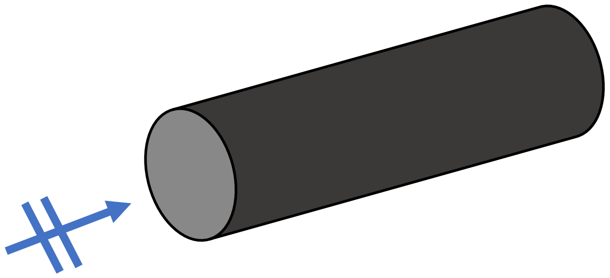
$$\frac{d\dot{E}_\kappa}{dx} = -\frac{1}{2}\omega AR\frac{\Im[-f_\kappa]}{|1-f_\kappa|^2}|\tau_1|^2$$

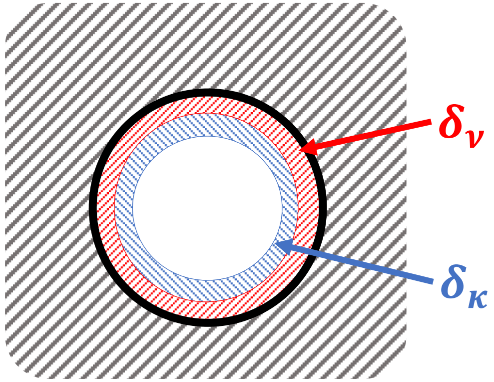
$$\dot{E}_{\kappa,\mathrm{tot}} = \int_L -\frac{1}{2}\omega AR\frac{\Im[-f_\kappa]}{|1-f_\kappa|^2}|\tau_1|^2\,dx$$

$$\dot{E}_{\kappa,\mathrm{tot}} = -\frac{1}{2r_\kappa}\int_L |\tau_1|^2\,dx$$

$$r_{\nu,\kappa} = r_{\nu,\kappa}(\text{fluid, geometry})$$

Thermoviscous behaviour





Viscous dissipation

$$\dot{E}_{\nu,\text{tot}} = -\frac{1}{2} r_\nu \int_L |U_1|^2 \, dx$$

$$\boldsymbol{r_\nu = \frac{\omega\rho_0}{A} \frac{\Im[-f_\nu]}{|1 - f_\nu|^2}}$$

$$f_\nu = 1 - \frac{\langle U_1 \rangle}{U_{1,\text{inv}}}$$

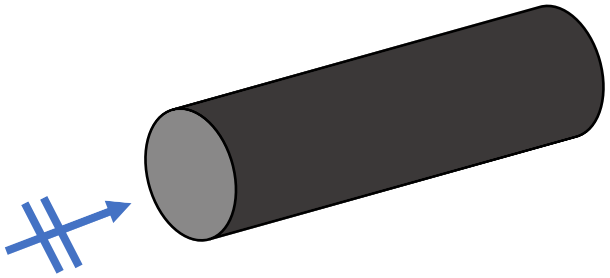
Thermal dissipation

$$\dot{E}_{\kappa,\text{tot}} = -\frac{1}{2 r_\kappa} \int_L |\tau_1|^2 \, dx$$

$$\boldsymbol{\frac{1}{r_\kappa} = \omega A R \frac{\Im[-f_\kappa]}{|1 - f_\kappa|^2}}$$

$$f_\kappa = 1 - \frac{\langle \tau_1 \rangle}{\tau_{1,\text{ad}}}$$

Thermoviscous behaviour



Viscous dissipation

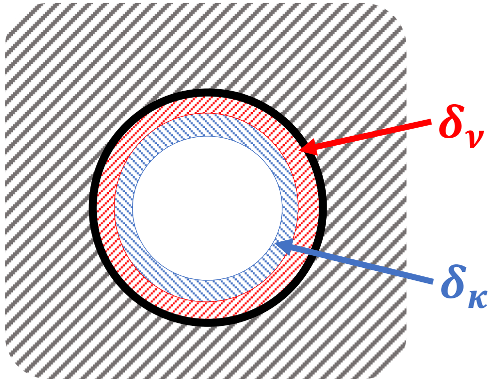
$$\dot{E}_{\nu,\mathrm{tot}} = -\frac{1}{2} r_\nu \int_L |U_1|^2 \, dx$$

$$\boldsymbol{r_\nu = \frac{\omega\rho_0}{A} \frac{\Im[-f_\nu]}{|1 - f_\nu|^2}}$$

Thermal dissipation

$$\dot{E}_{\kappa,\mathrm{tot}} = -\frac{1}{2r_\kappa} \int_L |\tau_1|^2 \, dx$$

$$\boldsymbol{\frac{1}{r_\kappa} = \omega A R \frac{\Im[-f_\kappa]}{|1 - f_\kappa|^2}}$$



$$f_\nu = 1 - \frac{\langle U_1 \rangle}{U_{1,\mathrm{inv}}}$$

$$f_\kappa = 1 - \frac{\langle \tau_1 \rangle}{\tau_{1,\mathrm{ad}}}$$

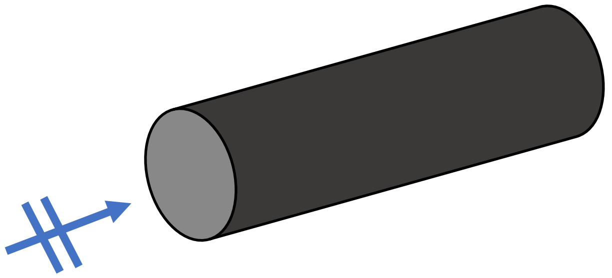
→

$$\tilde{\rho} = \frac{\rho_0}{1 - f_\nu}$$

$$\widetilde{K} = \frac{\gamma p_0}{1 + (\gamma - 1) f_\kappa}$$

Dragonetti, R. et al. (2016). Modeling energy conversion in a tortuous stack for thermoacostic applications. *Applied Thermal Engineering*, *103*, 233–242.

Thermoviscous behaviour



Viscous dissipation

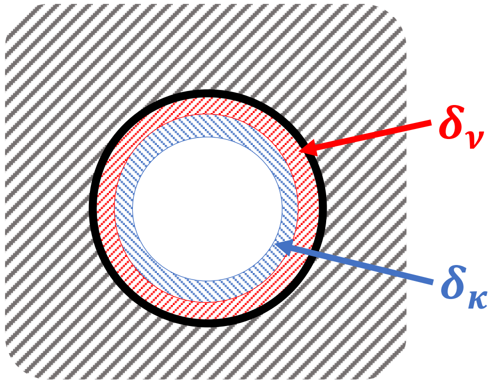
$$\dot{E}_{\nu,\mathrm{tot}} = -\frac{1}{2} r_\nu \int_L |U_1|^2 \, dx$$

Thermal dissipation

$$\dot{E}_{\kappa,\mathrm{tot}} = -\frac{1}{2 r_\kappa} \int_L |\tau_1|^2 \, dx$$

CIRCULAR PORES

$$f_{\nu,\kappa} = \frac{2 J_1\left[(i-1) r_0/\delta_{\nu,\kappa}\right]}{J_0\left[(i-1) r_0/\delta_{\nu,\kappa}\right](i-1) r_0/\delta_{\nu,\kappa}}$$

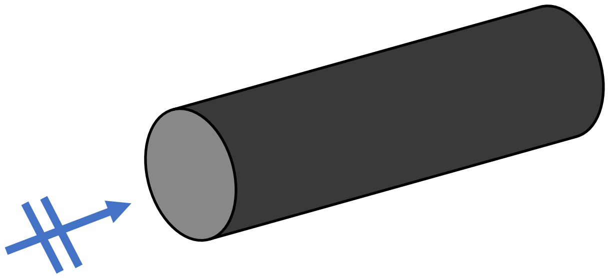


COMPLEX MICRO-GEOMETRY

$$f_\nu = 1 - \frac{1}{\alpha_\infty\left(1 - \frac{i}{\tilde{\omega}_\nu}\sqrt{1 + i\frac{M}{2}\tilde{\omega}_\nu}\right)}, \quad f_\kappa = 1 - \frac{1}{1 - \frac{i}{\tilde{\omega}_\kappa}\sqrt{1 + i\frac{M'}{2}\tilde{\omega}_\kappa}}$$

Di Giulio, E., Nguyen, C. T., Perrot, C., & Dragonetti, R. (2023). Wire mesh stack and regenerator model for thermoacoustic devices. *Applied Thermal Engineering*, *221*, 119816.

Thermoviscous behaviour

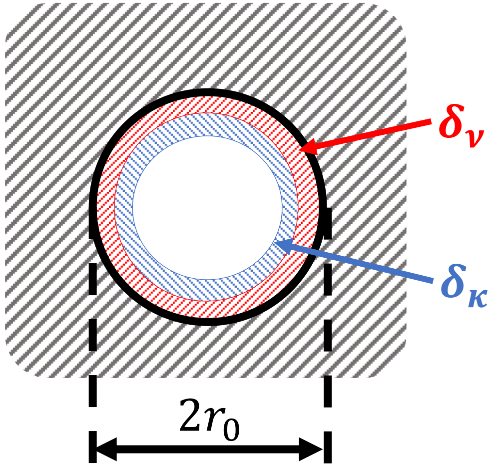


Viscous dissipation

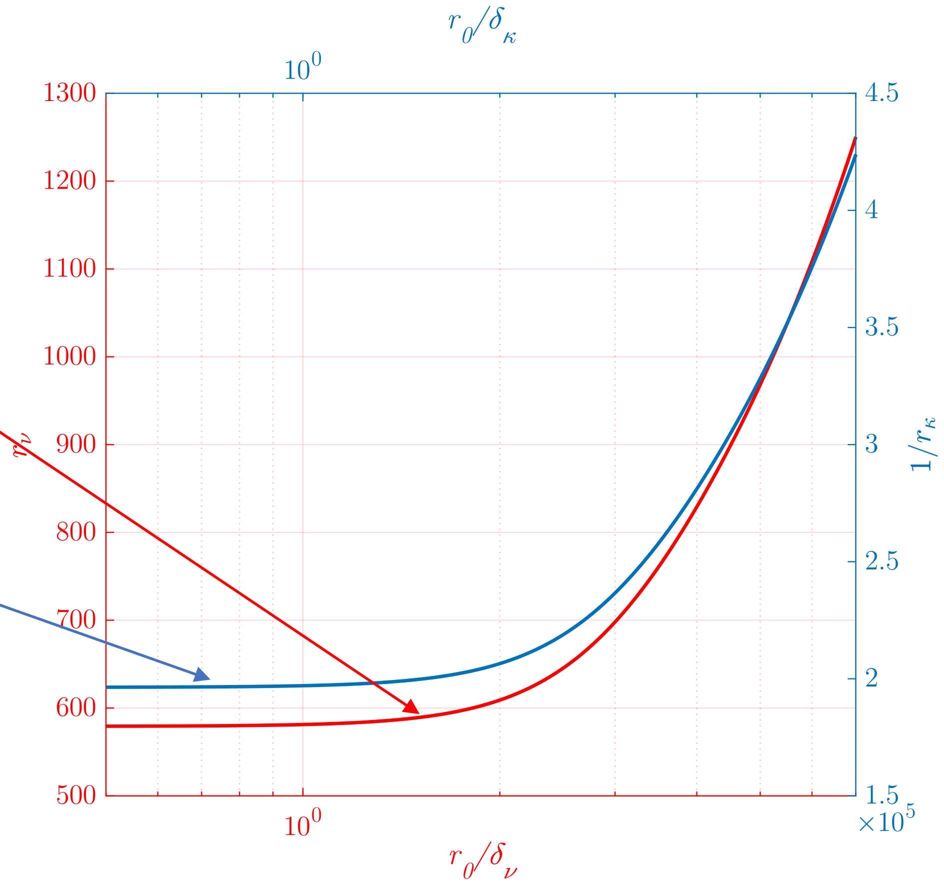
$$\dot{E}_{\nu,\mathrm{tot}} = -\frac{1}{2} r_\nu \int_L |U_1|^2 \, dx$$

Thermal dissipation

$$\dot{E}_{\kappa,\mathrm{tot}} = -\frac{1}{2 r_\kappa} \int_L |\tau_1|^2 \, dx$$



CIRCULAR PORES



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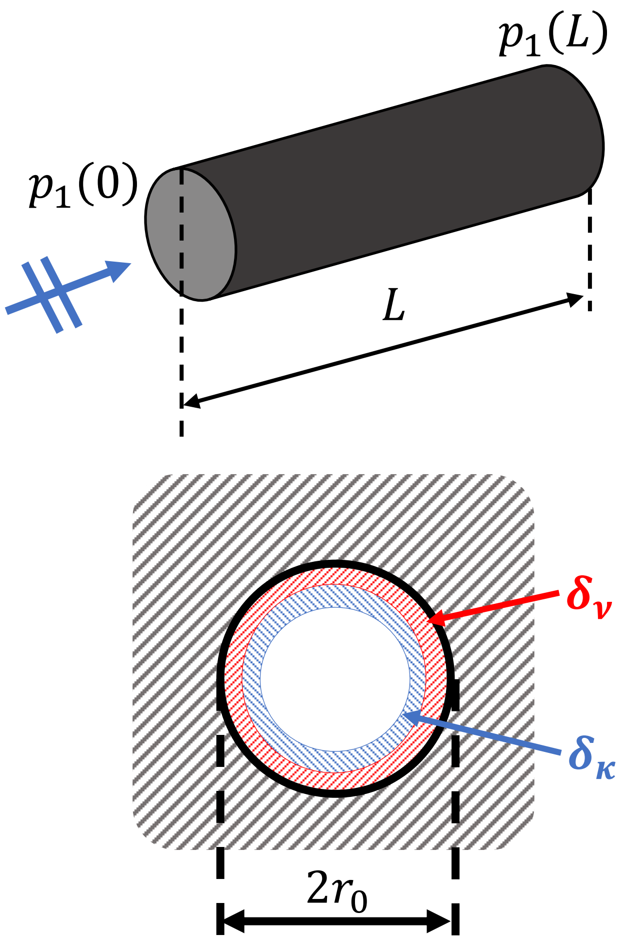
Acoustic fields inside a porous material: pressure, velocity, temperature



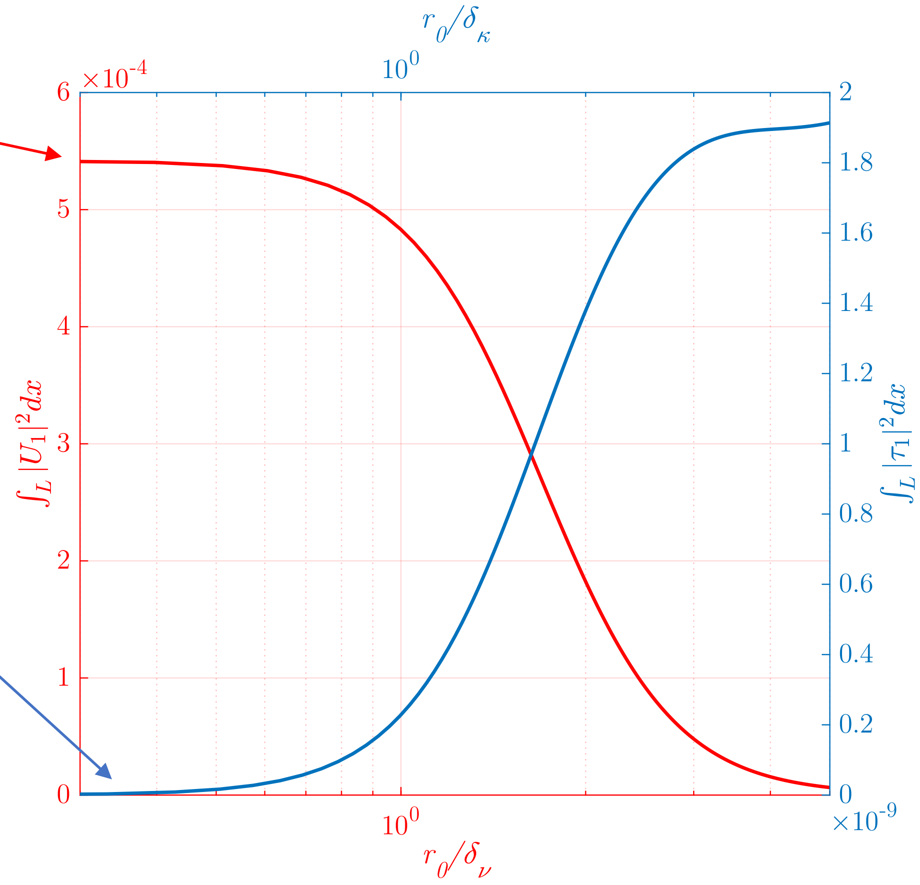
Viscous dissipation

$$\dot{E}_{\nu,\mathrm{tot}} = -\frac{1}{2} r_\nu \int_L |U_1|^2 \, dx$$

Thermal dissipation

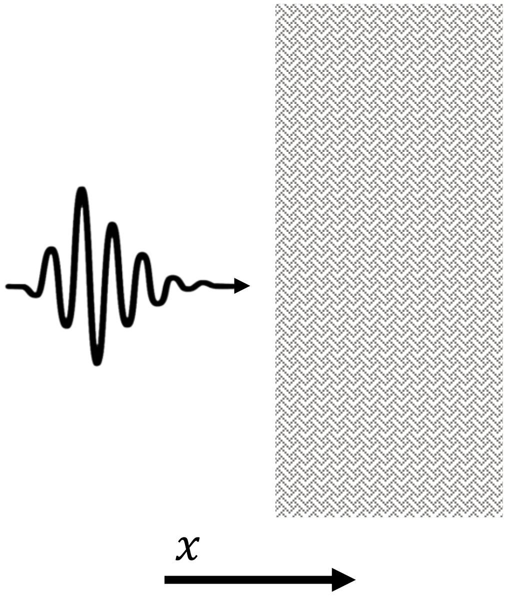
$$\dot{E}_{\kappa,\mathrm{tot}} = -\frac{1}{2 r_\kappa} \int_L |\tau_1|^2 \, dx$$

CIRCULAR PORES



Acoustic fields inside a porous material: pressure, velocity, temperature

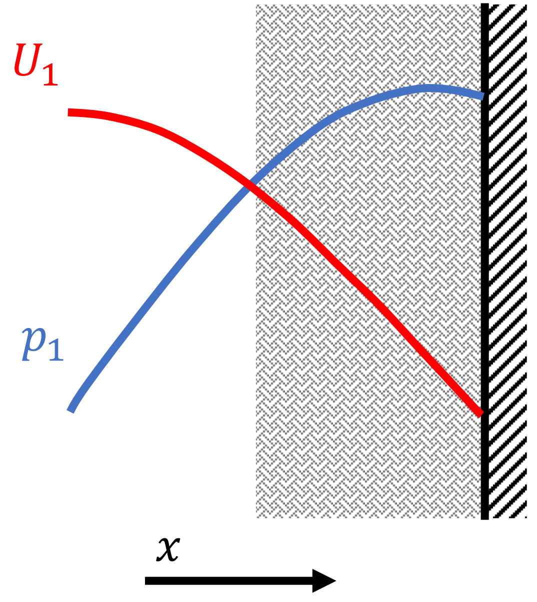
$$\frac{d\dot{E}}{dx} = -\frac{1}{2} r_\nu |U_1|^2 - \frac{1}{2 r_\kappa} |p_1|^2 + \Re[g \tilde{p}_1 U_1]$$



Acoustic fields inside a porous material: pressure, velocity, temperature

$$\frac{d\dot{E}}{dx} = \frac{1}{2r_\kappa}(\Gamma - 1)|p_1|^2 - \frac{1}{2}r_\nu|U_1|^2$$

$$\Gamma = \frac{\nabla T}{\nabla T_{\mathrm{crit}}} \qquad \nabla T_{crit} = \frac{A\omega|p_1|}{\rho_0 c_p|\mathrm{U}_1|}$$



$$\Gamma = 0$$

Pure dissipation
Sound absorption case

$$\frac{d\dot{E}}{dx} = -\frac{1}{2r_\kappa}|p_1|^2 - \frac{1}{2}r_\nu|U_1|^2$$

$$\alpha = \frac{\dot{E}}{\dot{E}_{\mathrm{inc}}} = \frac{\int_L \left(\frac{d\dot{E}}{dx}\right) dx}{\dot{E}_{\mathrm{inc}}}$$

$$\frac{d\dot{E}}{dx} = \frac{d\dot{E}_\kappa}{dx} + \frac{d\dot{E}_\nu}{dx}$$

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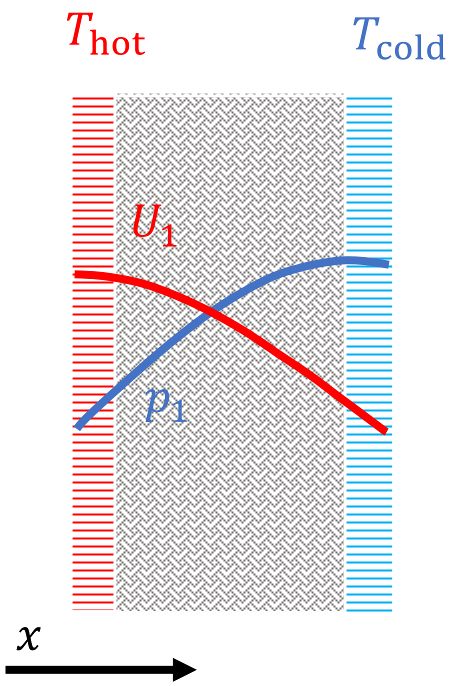
Acoustic fields inside a porous material: pressure, velocity, temperature

$$\frac{d\dot{E}}{dx} = \frac{1}{2r_\kappa}(\Gamma - 1)|p_1|^2 - \frac{1}{2}r_\nu|U_1|^2$$

$$\Gamma = \frac{\nabla T}{\nabla T_{\text{crit}}}$$



$\Gamma \neq 0$

Thermoacoustic case

$$\frac{d\dot{E}}{dx} > 0$$

$$\frac{d\dot{E}_\kappa}{dx} = \frac{1}{2r_\kappa}(\Gamma - 1)|p_1|^2$$

$$\frac{d\dot{E}_\nu}{dx} = -\frac{1}{2}r_\nu|U_1|^2$$

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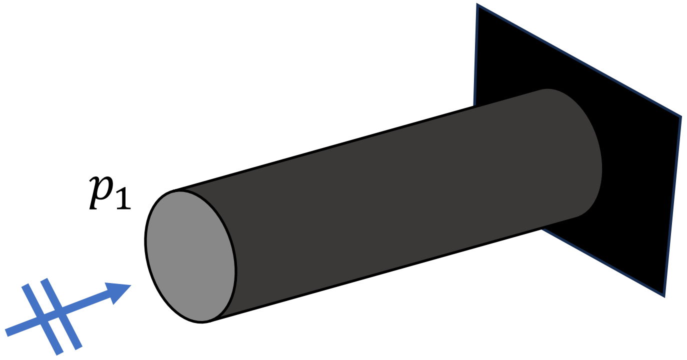
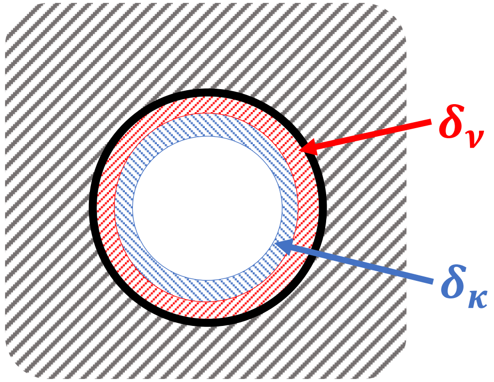
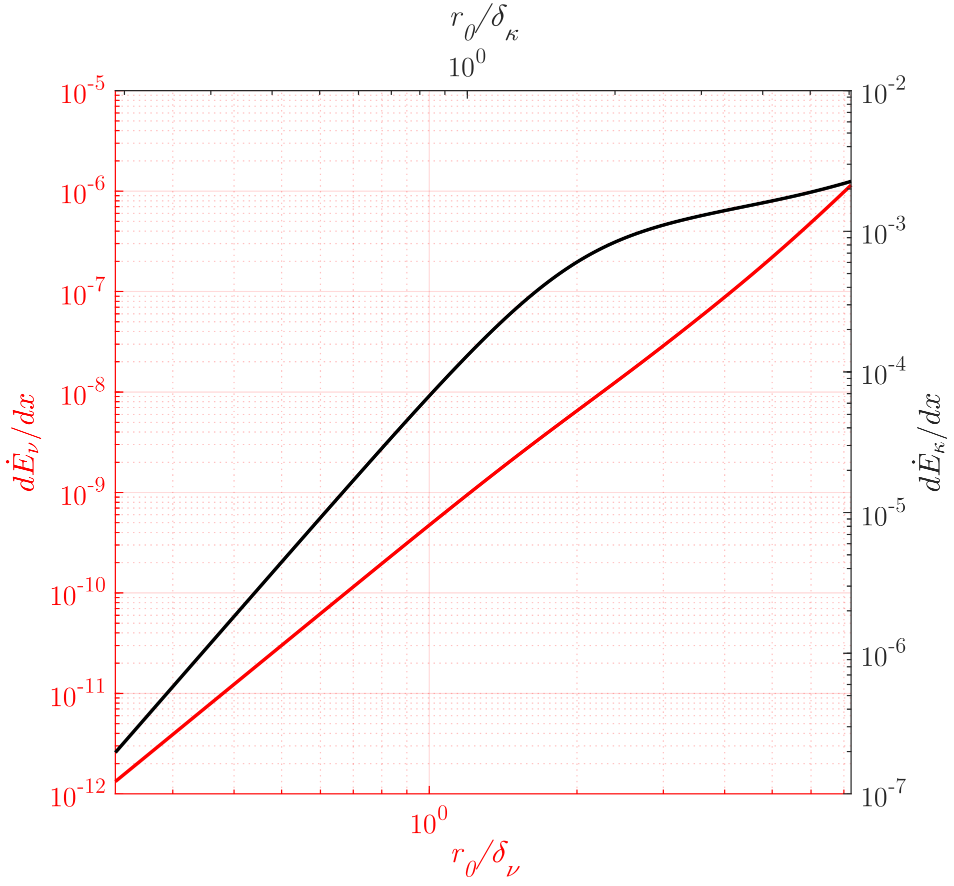
Geometry design to control viscous and thermal phenomena





$\dot{E}_\nu$ ⟷ $\dot{E}_\kappa$

One Parameter: r_0



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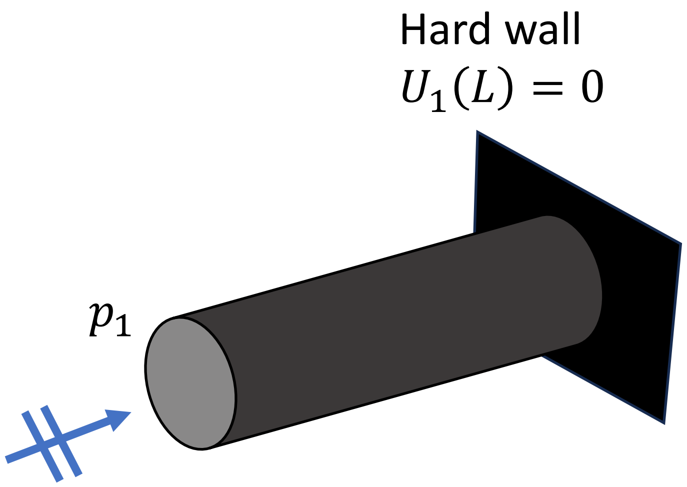
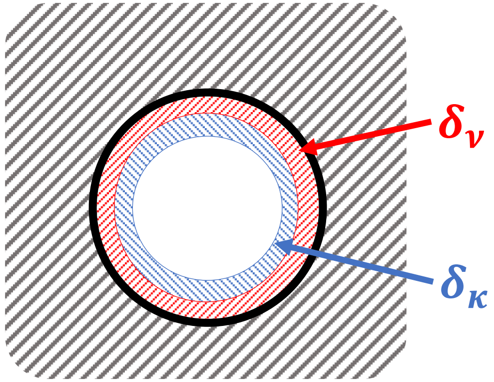
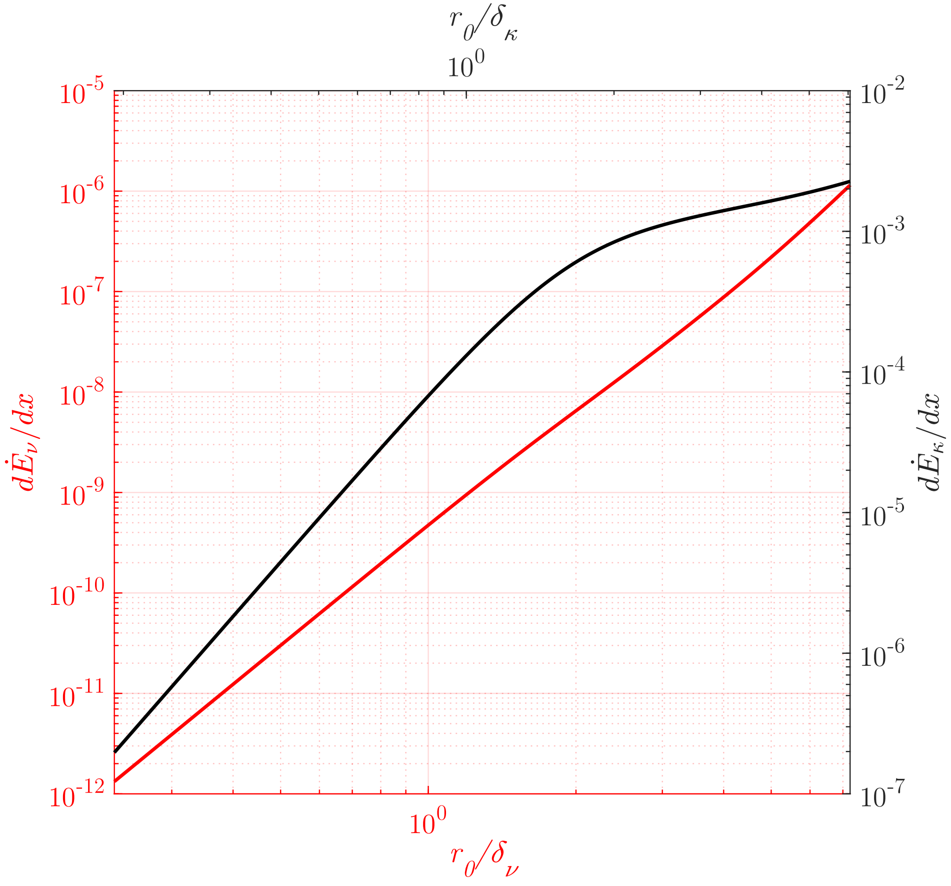
Geometry design to control viscous and thermal phenomena





One Parameter: r_0



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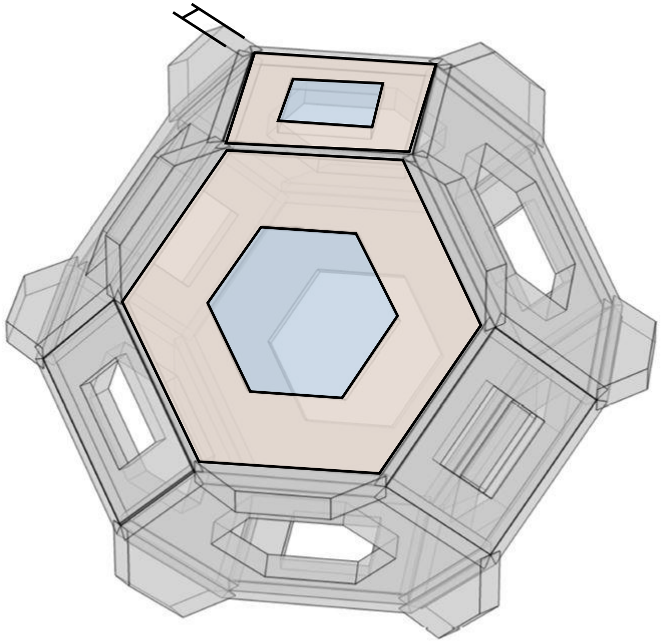
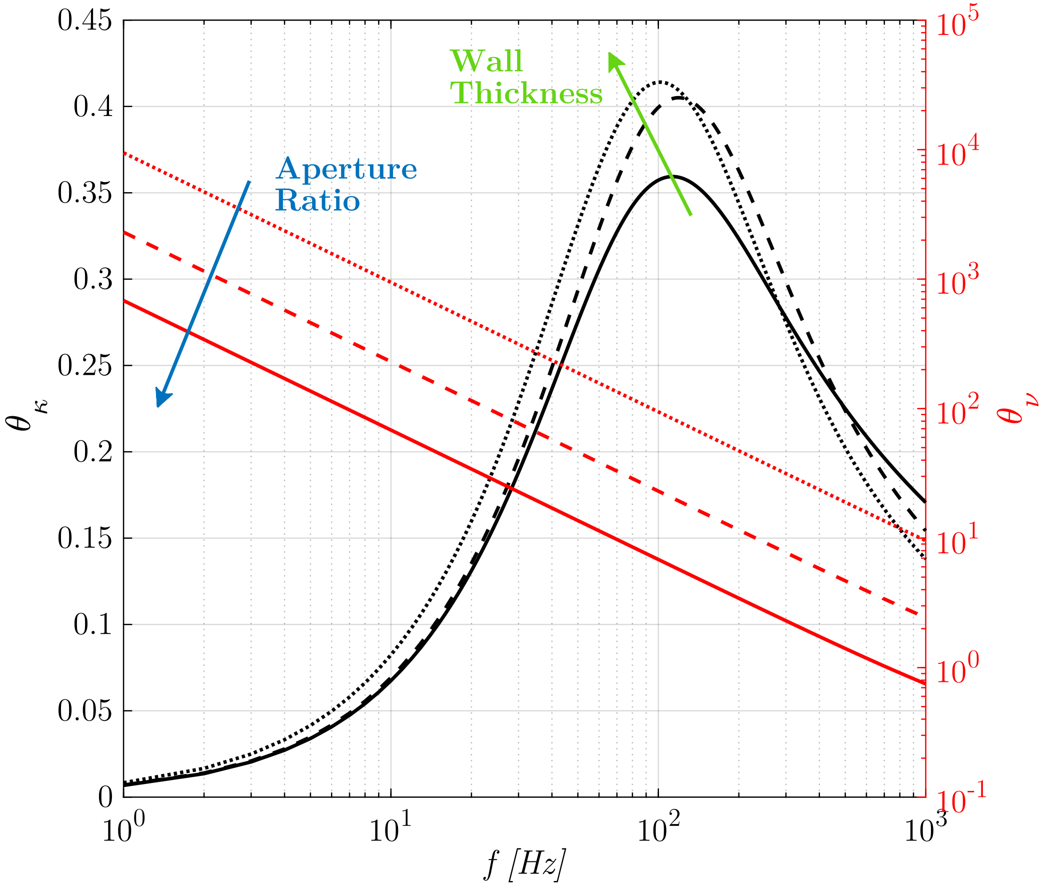
Geometry design to control viscous and thermal phenomena



$\dot{E}_\nu$ $\dot{E}_\kappa$

More Degrees of Freedom



Thank you for your attention