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COMSOL
CONFERENCE
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Modelling the Dynamic Viscous and Thermal Dissipation Mechanisms in a Fibrous Porous Material

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Presentation Outline

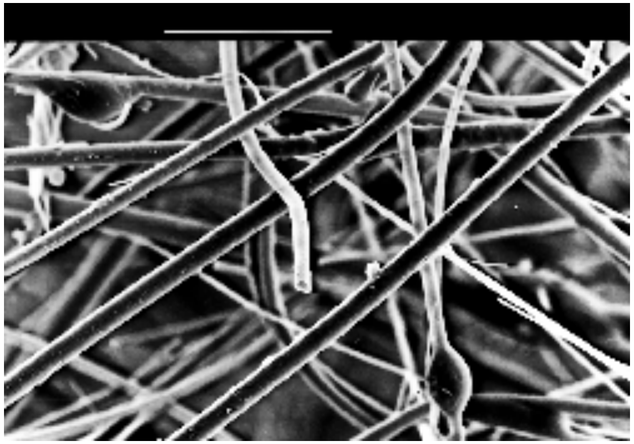
- New poroelastic fibre microstructure material model with analytical viscous drag force and heat transfer expressions for cylindrical fibres.

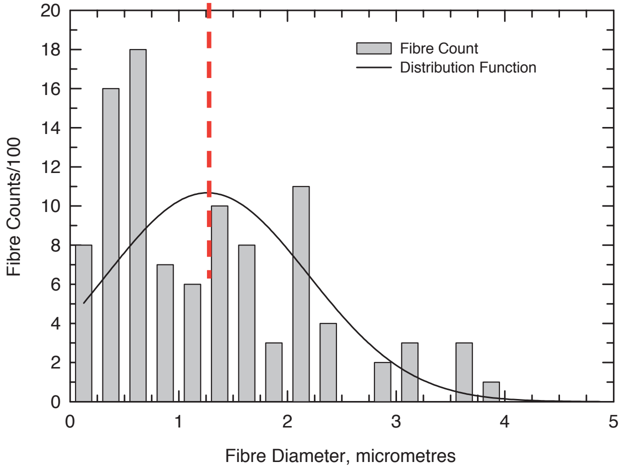
- Based only on geometrical properties of the material, and constitutive properties of the solid fibres and surrounding fluid.

- Includes diameter and fibre orientation distributions, which are tied closely to material production methods.

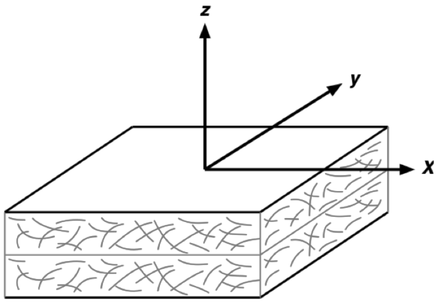
- Utilize COMSOL thermoviscous acoustic fluid FE models as a *Virtual Laboratory*, to verify the assumption of no viscous and thermal boundary layer interaction between neighbouring fibres.

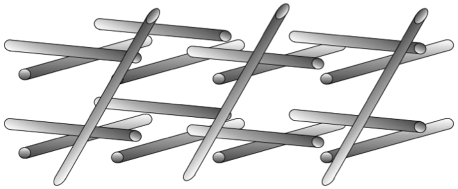
Transversely Isotropic Fibre Assumption





- 10 kg/m^3 bulk density glassfibre aircraft thermal insulation
- 1.28 micron mean fibre diameter





- Transversely isotropic (stacked isotropic layers with some fibres orientated vertically)

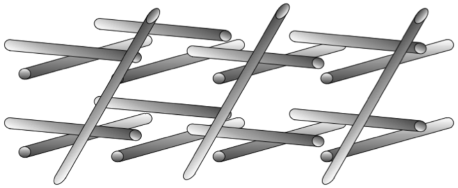
Momentum Equations in Terms of Viscous Drag Forces

Solid Momentum Equations

$$\phi\rho_s\ddot{u}_i = \left(\frac{\partial\sigma_{ii}}{\partial x_i}+\frac{\partial\sigma_{ij}}{\partial x_j}+\frac{\partial\sigma_{ik}}{\partial x_k}\right) - F_{D_i}$$

Fluid Momentum Equations

$$\left(1-\phi\right)\rho_f\ddot{U}_i = \frac{\partial\sigma}{\partial x_i} + F_{D_i}$$



* Viscous Drag Force Impedance Matrix

$$\left\{\mathbf{F}_D\right\} = \left[\bar{Z}\right]\left\{\dot{\mathbf{u}}-\dot{\mathbf{U}}\right\}$$

relative motion between solid and fluid

$$\left[\bar{Z}\right] = \frac{\phi}{A}\begin{bmatrix} J & 0 & 0 \\ 0 & J & 0 \\ 0 & 0 & K \end{bmatrix}$$

transversely isotropic, isotropic or fully anisotropic

$$Z_l = 2\pi a k_\beta \mu_f \frac{H_1^{(2)}\left(k_\beta a\right)}{H_0^{(2)}\left(k_\beta a\right)}$$

longitudinal cylinder oscillations

$$\boxed{Z_t = j\pi\rho_f\omega a^2\left[1-\frac{4H_1^{(2)}\left(k_\beta a\right)}{k_\beta a H_0^{(2)}\left(k_\beta a\right)}\right]}$$

transverse cylinder oscillations

* defined in terms of diameter and fibre orientation distributions

Fluid Continuity with Heat Transfer from Fibre to Fluid

Stress-Strain for Transverse Isotropy

$$\{\sigma\}=[D]\{\varepsilon\}$$

Fluid Dilatation modified for Non-Equilibrium (heat flow from fibres to fluid results in thermal expansion of the fluid)

$$\chi\sigma = R\varepsilon + \left(Me_{xx} + Me_{yy} + Qe_{zz}\right)$$

Scaling Coefficient

$$\chi = \left[1 - \frac{\alpha\eta R}{j\omega\rho_f Cp_f (1-\phi)}\right]$$

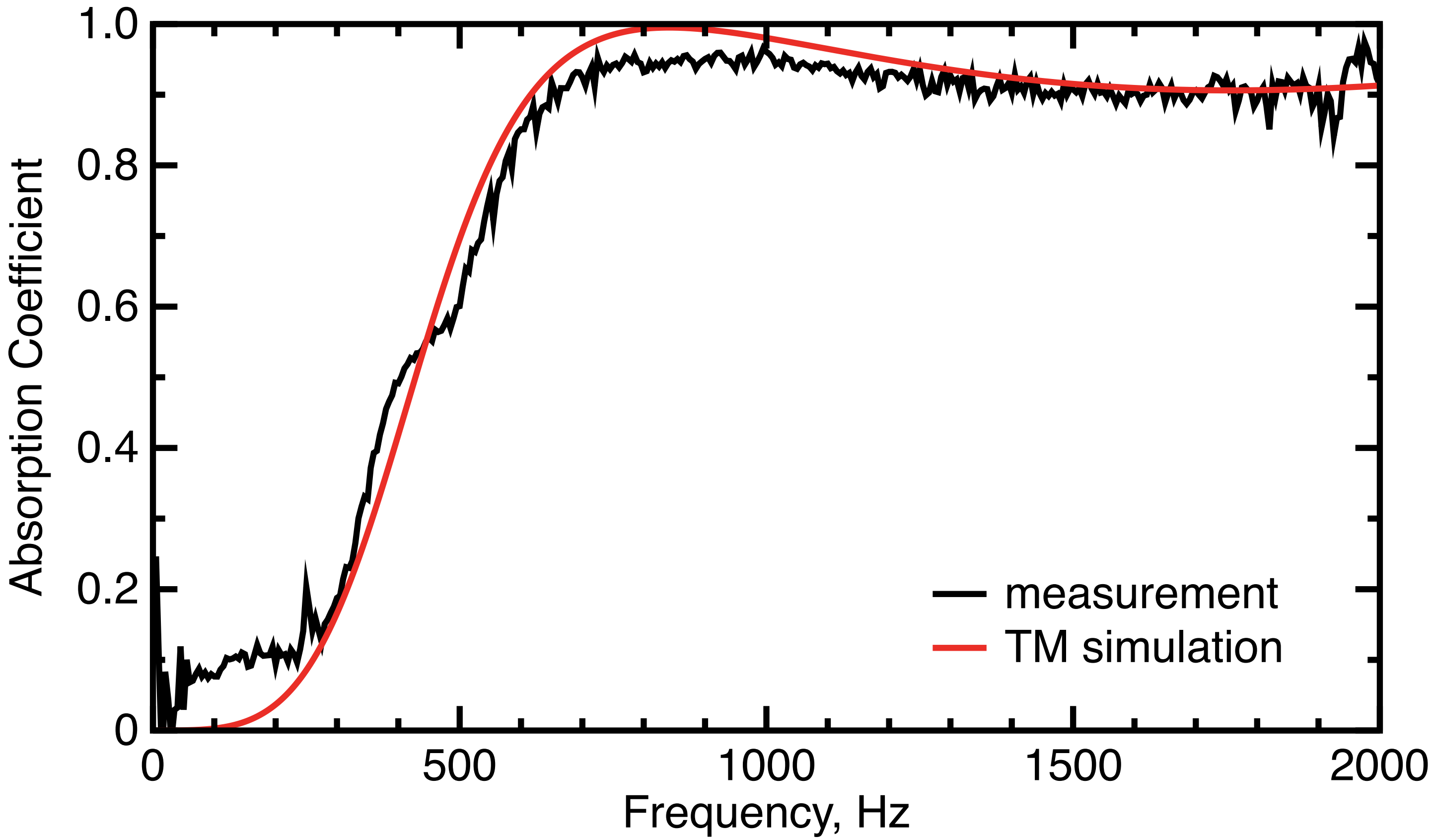
$$\alpha = \eta T_f' \left\{ \frac{\rho_f Cp_f (1-\phi)}{\bar{Y}_e} + \frac{1}{j\omega} \right\}^{-1}$$

Thermal Impedance at fibre/fluid interface

$$\bar{Y}_e = \frac{\phi}{A}\left[\frac{1}{Y_f} + \frac{1}{Y_s}\right]^{-1}$$

based on oscillatory fluid and fibre thermal fields

Impedance Tube Sound Absorption



- Measurement: 50 mm sample thickness, rigid backing impedance tube.
- TM Simulation: 1.28 micron mean fibre diameter, assumed 50 deg. fibre inclination angle.

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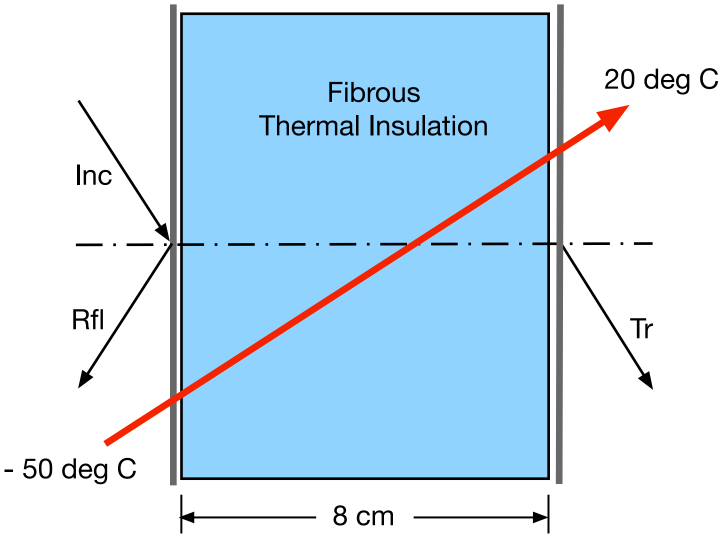
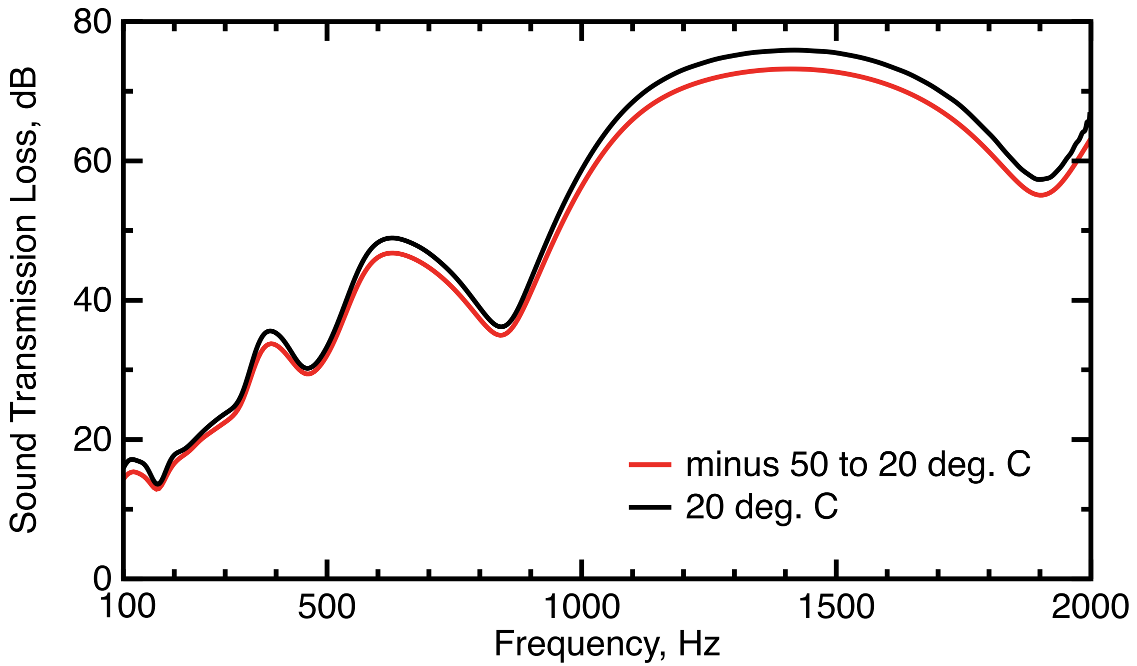
Sound Transmission Through Aircraft Fuselage with Temperature Gradient

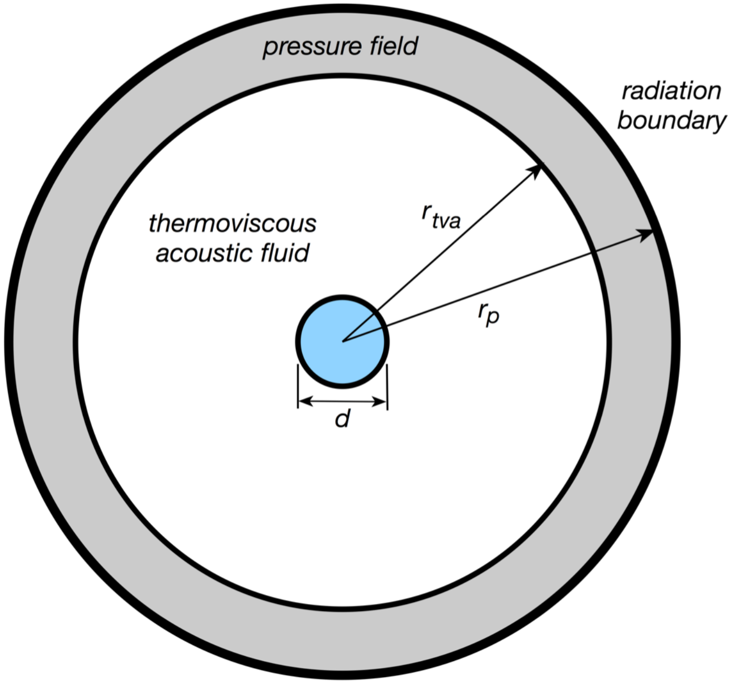


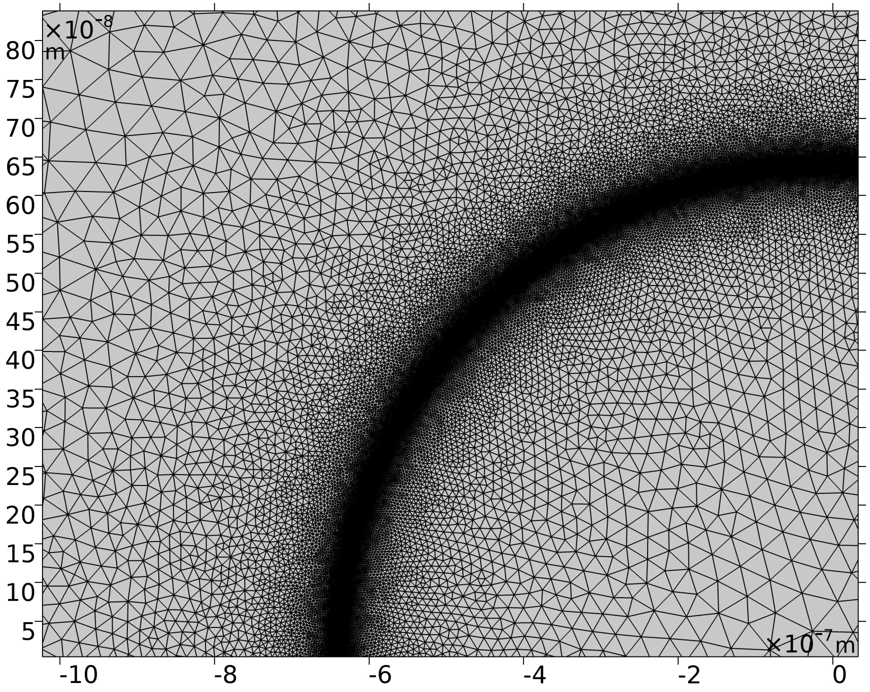


- Diffuse STL through an aircraft fuselage during inflight conditions.
- - 50 to 20 deg. C temperature gradient.
- Traditional room temperature analysis over-estimates acoustic performance.

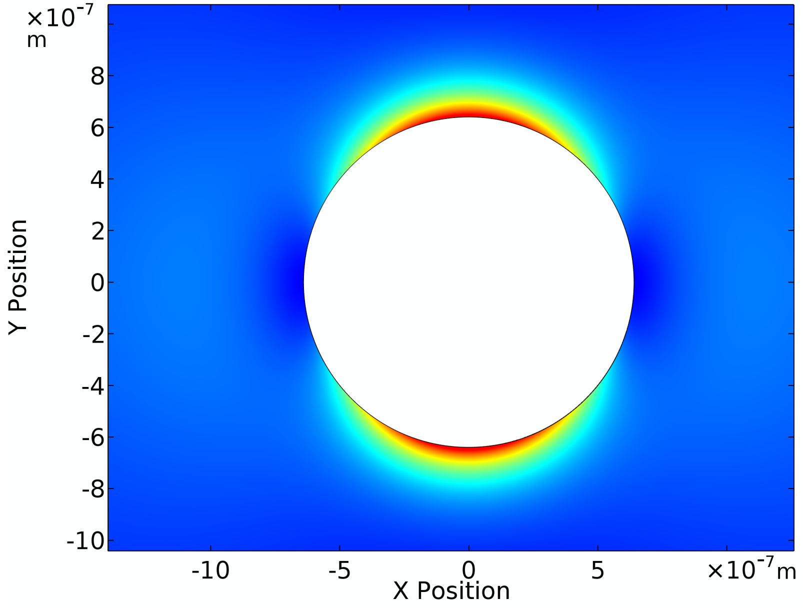
Thermoviscous Acoustic Fluid Modelling COMSOL as a *Virtual Laboratory*

- 1.28 micron solid cylinder, 0.01 micron transverse oscillations (@ 1 Hz)
- 15 mm thermoviscous fluid, 5 mm acoustic field with external radiation boundary (to ensure complete decay of radiating waves)
- internal stress field of fibre is modelled
- 12 million DOF, nanoscale element sizes along fibre boundary

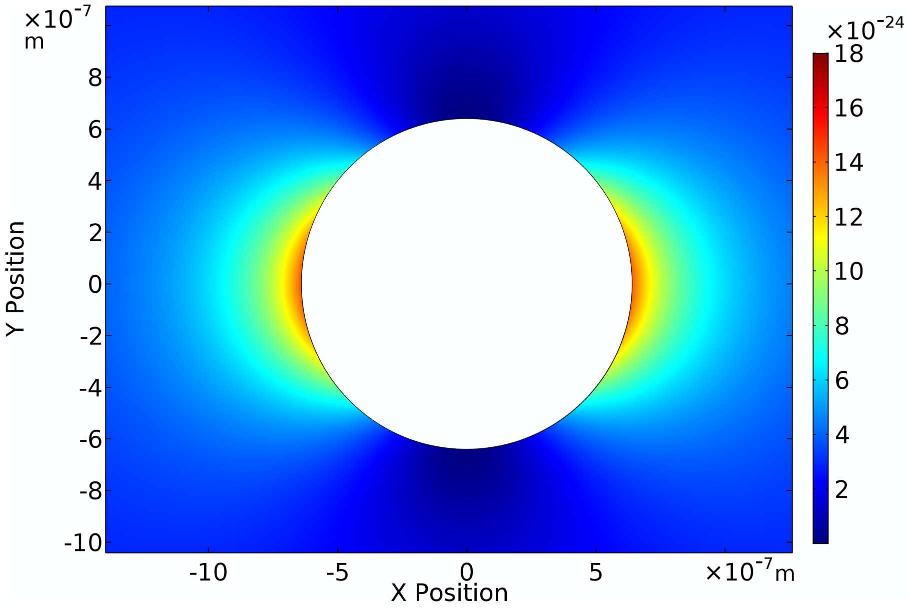




Viscous and Thermal Boundary Layers on a Single Fibre



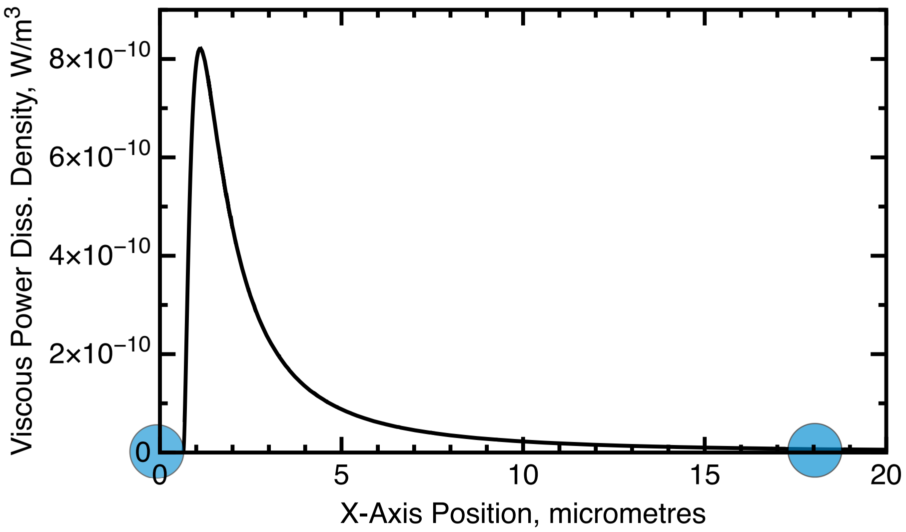
viscous



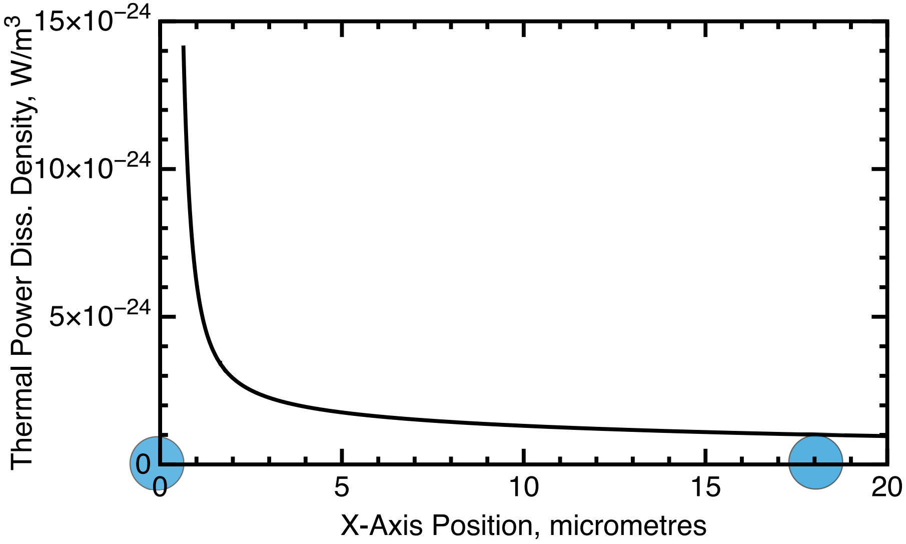
thermal

- Viscous and thermal boundary layers concentrated near fibre surface, at the micro and nano scale.
- Analytical transverse dynamic drag impedance: 87665 Ns/m^4 at 1 Hz.
- FE solution: 87642 Ns/m^4. 0.02% difference.

Viscous and Thermal Boundary Layer Strength



viscous

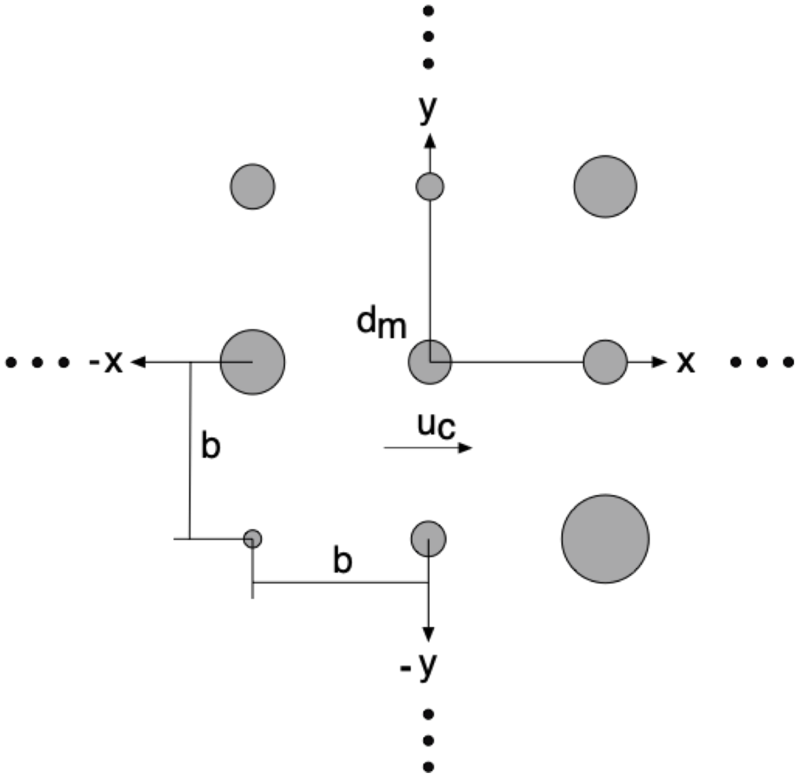


thermal

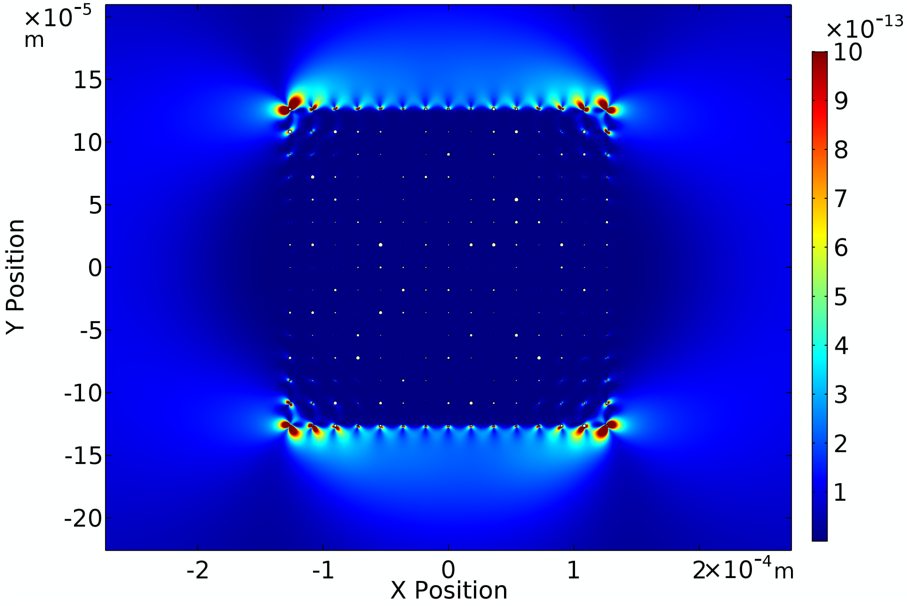
- Viscous dissipation effects dominate in the material.
- Boundary layer strengths are concentrated near fibre surface.
- Viscous boundary layer has dissipated 98% at the neighbouring fibre. Viscous boundary layer penetration depth is 2.2 mm at 1 Hz. Thermal is 2.6 mm.

Multifibre Array Modelling

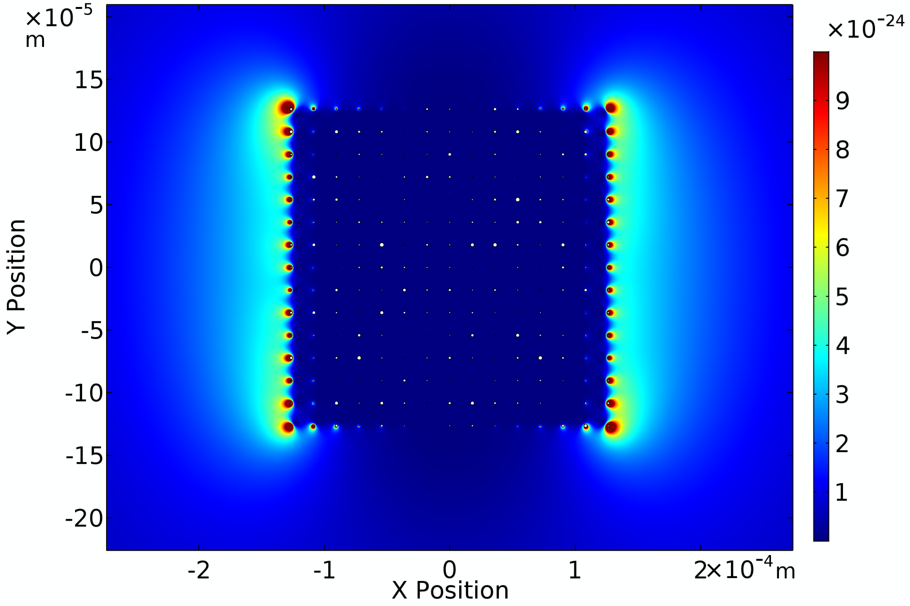
- 225 regularly spaced fibre array representative of diameter distribution.
- Allows viscous and thermal boundary layer interaction between fibres to be considered.
- 35 million DOF in model.



225 Fibre Array: Viscous and Thermal Boundary Layers Interaction



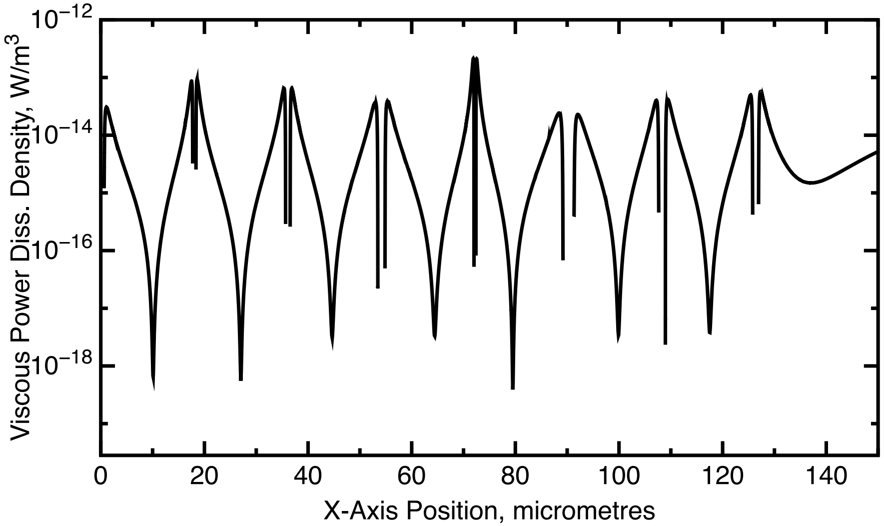
viscous



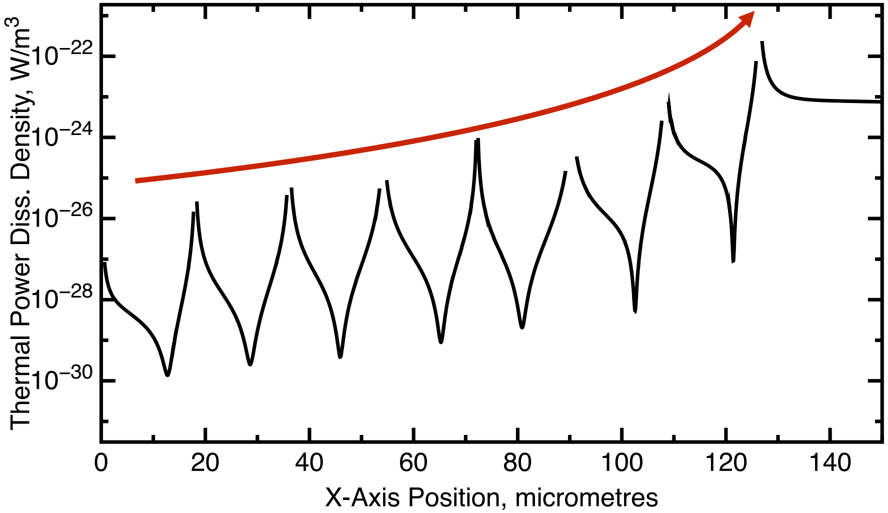
thermal

- Viscous drag force estimate within approx. 1.1% of analytical solution.
- Amplitude increases observed for outer thermal boundary fibres.

Viscous and Thermal Boundary Layers Along X-Axis



viscous



thermal

- Uniqueness of viscous boundary layer amplitudes – assume no significant interaction between fibre viscous boundary layers.
- Incremental scaling of thermal boundary layers amplitudes.

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Conclusions

- Poroelastic fibrous microstructure material model with analytical viscous drag force and thermal heat transfer expressions.
- Fibre diameter/orientation distributions, which are closely tied to material manufacturing processes.
- Acoustics vs temperature investigations.
- Traditional poroelastic transport properties are not required.
- COMSOL thermoviscous acoustic fluid simulations used as a *Virtual Laboratory* to confirm negligible interaction between the dominant viscous boundary layers.