Acoustic And Thermal Insulation Foam Modelling and Simulation for Space Craft

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Abstract

The basis of this project is the modelling and simulation of melamine foam and study of other acoustic and thermal insulation foams . The External Tank of rockets required insulation to maintain the cryogenic fuels, liquid hydrogen, and liquid oxygen as well as to provide additional structural integrity through launch and after release from the Orbiter. Sites for launching large rockets are commonly equipped with some sound suppression system for absorb or deflect acoustic energy produced during a rocket launch. As engine exhaust gasses exceed speed of sound, they will collide with ambient air and then shockwaves are created, with noise levels approaching 200 db. Also foam and insulation protects deep space rocket from fire and ice. The cryogenic fuel, made up of liquid hydrogen and liquid oxygen, that powers the rocket has to stay extremely cold to remain liquid

This project included the modelling and simulation of open foam materials having acoustic and thermal insulation properties. COMSOL Multiphysics has proven to be an invaluable virtual laboratory tool in assisting development of a new generation of efficient analytical models describing the acoustics of highly porous fibre and open-cell foam materials. From this project will get an idea for microstructural viscous energy dissipation, oscillatory heat transfer and elasticity towards the three-dimensional foam geometry through simulation software. very promising results for the Melamine foam material, and an excellent prediction of the acoustics of this open-celled porous foam material will be done through this project.

1.INTRODUCTION

Thermal insulation means the reduction of heat transfer which may occure between objects in thermal contact or in range of radiative influence. Acoustic Insulation is any kind of reducing the intensity of sound with respect to a specified source or receptor. Foams are best for thermal and acoustic insulation for rockets. There are different types of foams polyurethane foam, melamine foam, polyimide foam, polyisocyanurate foam.

Why rocket need thermal and acoustic insulation? Because the External Tank required insulation to maintain the cryogenic fuels, liquid hydrogen, and liquid oxygen as well as to provide additional structural integrity through launch and after release from the Orbiter. Sites for launching huge rockets are commonly equipped with a sound suppression system for absorb or deflect acoustic energy generated during a rocket launch. As engine exhaust gasses crosses the speed of sound, they collide with the ambient air and then shockwaves are created, with noise levels approaching 200 db. Also Foam and Cork Insulation Protects Deep Space Rocket from Fire and Ice. The cryogenic fuel, made up of liquid hydrogen and liquid oxygen, that powers the rocket has to stay extremely cold to remain liquid

The Space Shuttle design facing lots of thermal insulation challenges. The system not only had to perform well, it had to integrate with other subsystems. The Orbiter's surfaces were exposed to exceedingly high temperatures and needed reusable, lightweight, low-cost thermal protection. The vehicle also required low vulnerability to orbital debris and minimal thermal conductivity Porous foam materials with high porosity are used as part of multi-layer panels for sound insulation and absorption in transportation vehicles. The acoustic properties of the foam are highly dependant on the micro geometry of the foam cells. In this work, simplified analytical models for calculating the viscous dynamic drag forces, and oscillatory heat transfer within fibrous materials have been adapted towards foam materials having micro-cell geometries composed primarily of cylindrical struts. The analytical results are compared to full visco thermal numerical models of an isotropic unit foam cell, For both high porosity foam and low porosity foam examples with typical dimensions for 3D printed materials, the agreement between analytical and thermo viscous numerical models is shown to be very good. This approach model can easily be extended to anisotropic materials as well **[5].** Here the melamine foam modelling and simulation is doing. Because it have lots of unique properties like Fire resistance (without addition of flame retardants)**,**High sound absorption **,** Application temperature up to 250ºC**,** Stable chemical and physical performance from -150ºC to 200ºC **,** Excellent thermal insulation **,** One of the lightest foam in the world.

Melamine formaldehyde (MF) foam is kind of fire-retardant material and has great potential in acoustic and thermal insulation area. . It is a kind of open-cell thermosetting and eco friendly foam and has attracted much attention all over the world. Because of its properties as the low density, corrosion resisting, good autologous fire-re- tardancy and high thermal stability it can be used for a long time in the environment of temperature as high as 150°C. Only several companies including BASF, Illtec and Zhong Yuan Da Hua CO. can produce flexible MF foam. Melamine foam was specially developed for insulating cabins and the ductwork in aircraft. It weighs just six grams per liter, which makes Melamine Foam is 30 percent lighter than conventional Melamine Foam . This means it is possible to fulfill the rising demands on noise, safety and increasingly lower weight in aircraft construction; at the same time, Melamine Foam meets the stringent fire safety standards set by the aviation authorities

2. Experimental and theoretical methodologies

2.1 Foam preparation

(i) Materials required

Melamine (99%), formaldehyde(37%), NaOH, petroleum ether (30~60℃), dimethyl silicone oil (H-201), tween-80, Octyl phenol ethoxylates (OP-10) and sodium dodecylbenzenesul- fonate (SDBS), acetic acid

(ii) Preparation of melamine foam

Melamine and 37% formaldehyde with the molar ratio of 1:3 were added to flask with three necks equipped with motor stir- rer, thermometer and condenser and heated to about 60℃ and then kept for a some minutes until the solution became clear one. Then 10%NaOH was dripped to adjust the pH of the solution to 8.5, and emulsifier can be added with the mass ratio 2% of the resin. And then the solution was kept to the temperature of about 85 ℃ for properly 2~3h till the viscosity of the system up to 2000 cm•Pa and cooled to room temperature and MF resin was ob- tained. Took a certain amount of MF resin and about 3% acetic acid and 10% petroleum ether the mass ratio of the MF resin together were added and agitated vigorously to uniform and put into the microwave oven to foam without restraint of volume for about 5 min. Finally the MF foam was put into air oven at 120℃ to wipe off water, residual formaldehyde and for further cross-linking to transfer ether bond to methylene [6]

2.2 Modeling equation

(i) Melamine Foam Unit Cell

For modeling of unit cell, need the dimensions of the unit cell and volume equation and porosity equations

For this development, the cells of the Melamine foam are represented as a simple iso-parametric, Kelvin-Cell like foam structure [5]. Each cell has a length of 0.283 mm (x, y, z-dir.), with the assumed cylindrical struts having a diameter of 5 microns, and a length of 0.100056 mm (point-to-point between the strut joints). Due to the hexagonal geometry of the cell, the oriented struts are assumed to have an off-axis alignment angle of 60 degrees. These geometric properties have been chosen to be representative of typical Melaminefoam materials, but have not been specifically measured.

(a). Volume of the foam cell can calculate using a relation for iso-parametric kelvin cell

$$V = 8\sqrt{2}L^3 \quad (1)$$

(b). The porosity of the foam can be defined as

$$\emptyset = 1 - (Vs/V) \quad (2)$$

Where the Vs is the solid volume and V is the total volume.

(ii). Microscopic Cell Elasticity

Assumption – assuming that the Melamine foam cell has isotropic cubic symmetry and cylindrical struts. The respective effective longitudinal Young's modulus and Poisson's ratio can be estimated using the following relations.

$$E = (11N + 4M)/(2\sqrt{3L} * (10N^2 + 31NM + 4M^2)) \quad (3)$$

$$\mathrm{Pr} = \frac{(\mathrm{N-M})(5\mathrm{N}+4\mathrm{M})}{(10\mathrm{N}^2+31\mathrm{NM}+4\mathrm{M}^2)} \quad (4)$$

Where $q^2 = A/(4\Pi)$, (5)

M= L/(EA) and (6)

$N = L^3/(3EAq^2)$ (7)

Here, *E* is the strut modulus, *L* is the length of the strut and *A* is the cross-sectional area. From these equations the young's modulus and Poisson's ratio will get.

Non equilibrium fluid dilation - Stress and strain for any porous material are related by coupled constitutive stress-strain relations of the form

$$\sigma = D * \varepsilon \quad (8)$$

Where the D is stiffness matrix.

Young's modulus and Poisson's ratio can be estimated for input into the stiffness matrix

(iii). Dynamic viscous drag force - The viscous drag losses arising in the interior of a porous material are important for its acoustic performance. Begin with solid and fluid momentum equation [1]

$$\emptyset\rho_s U = \left(\frac{\partial\sigma ii}{\partial xi} + \frac{\partial\sigma ij}{\partial xj} + \frac{\partial\sigma ik}{\partial xk}\right) - Fdi \quad (9)$$

But Kelvin cell foam material allows the equation of motion of the viscous fluid. The fluid momentum equation is defined as

$$(1-\emptyset)\rho_f \mathrm{U} = \frac{\partial\sigma}{\partial \mathrm{xi}} + \mathrm{Fdi} \quad (10)$$

Where the Ø is the porosity, ρ_s is the density of solid and ρ_f is the density of fluid, Fdi is the component of the volume averaged dynamic viscous drag force vector Fd.

$$F_d = Z_{LT} Vex \quad (11)$$

Where Z_{LT} is the dynamic viscous drag force impedance (both longitudinal and transverse) and Vex is the solid frame excitation velocity.

Assume the solid struts of open cell foams are cylindrical and are isotropic melamine foam cell.

Then the viscous drag force impedance matrix of the cell, Zcell is defined as follows

$$Zcell = \frac{(1-\emptyset)}{V} \sum_{n=1}^{N} Rn\ [Z_{LT}]\ R_n^T \quad (12)$$

Where the R is the foam cell alignment rotation matrix.

(iv). Oscillatory heat transfer effect - oscillatory heat transfer occurs between the solid phase and the surrounding viscous fluid, resulting in a thermal expansion of the fluid. This will leads to an extension of the fluid dilatation terms (equation 8) of the stress strain relations away from equilibrium in isotropic case is

$$X\sigma = R\varepsilon + Q(e_x + e_y + e_z) \quad (13)$$

Where X is the frequency dependent thermal coefficient and R and Q are coefficients of the stiffness matrix. Where X is

$$X = [1 - \frac{\alpha\mu R}{j\omega\rho_f C_p \emptyset}] \quad (14)$$

Where $$\alpha = \mu T_f \div (\frac{\rho_f C_p \emptyset}{Ye} + \frac{1}{j\omega}) \quad (15)$$

The T_f is the fluctuating fluid temperature and the Ye is the effective thermal impedance function. It can be calculated as follows

$$Ye = \frac{(1-\emptyset)}{A} \div \left[\frac{1}{Yf} + \frac{1}{Ys}\right] \quad (16)$$

Yf for fluid phase and Ys for solid phase which can be defined as

$$Yf = 2\pi r_s k_f \frac{H1^2 kr_s}{H0^2 kr_s} = \frac{q}{T(r=r_s)} \quad (17)$$

$$Ys = -2\pi r_s k_s \frac{j1Kr_s}{j0Kr_s} = \frac{q}{T(r=r_s)} \quad (18)$$

Where q is

$$q = \int_0^{2\pi} q' r_s d\theta = 2\pi r_s q' \quad (19)$$

$$q' = -k_f \frac{dT}{dr} \quad (20)$$

Where the q' is the heat transfer rate.

2.3 Simulation using comsol multiphysics

2.3.1 Unit cell formation.

Using specifications build the 3Dimentional form of unit cell.

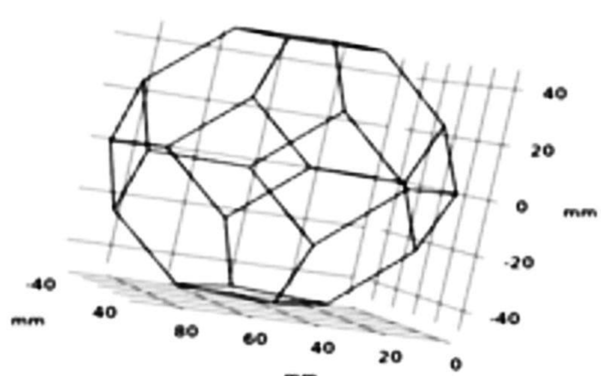

Fig.1. Simulation of melamine foam unit cell

2.3.2 Elasticity matrix estimation

Add the equation 3 to 8 in equation tab or select equations from solver. Add the parameters given in unit cell formation. Get result.

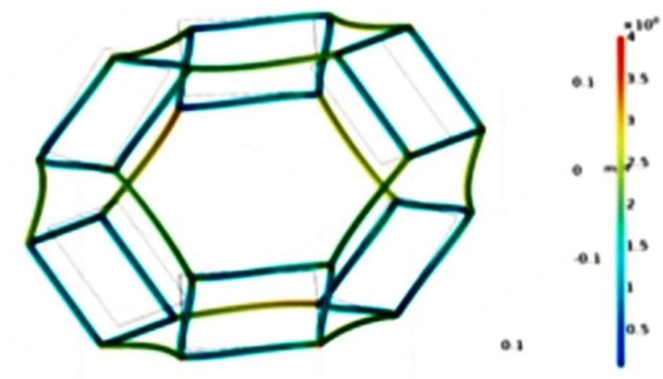

Fig.2. the elasticity matrix estimation

2.3.3 Simulation of dynamic viscous drag force

For simulation of dynamic viscous drag force, we have to select Thermo viscous acoustics analysis (TVA) feature of COMSOL Multiphysics

After selecting this mode import the melamine foam cell model, which is already modeld till elasticity matrix then select the thermo viscous acoustic equation and add the equations 9 to 12. Then create a fluid layer over the cell. Then set the sound pressure level settings as user defined pressure or any reference pressure and get result. The struts must oriented at 60 degree due to hexagonal configuration.

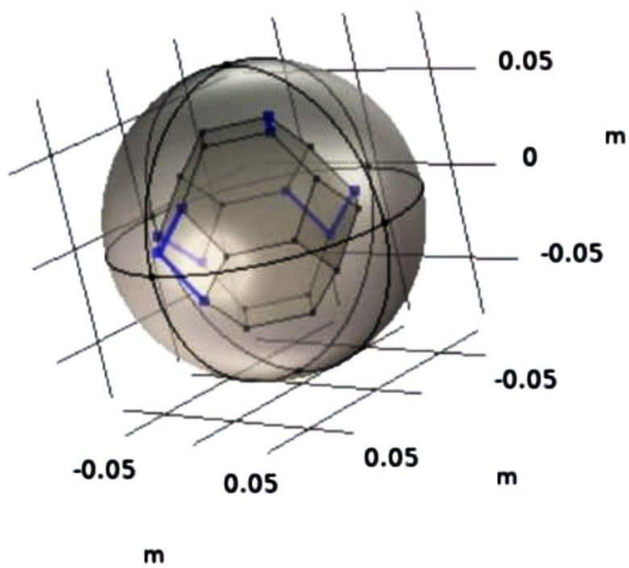

Fig . 3. unit cell surrounded by fluid layer TVA simulation.

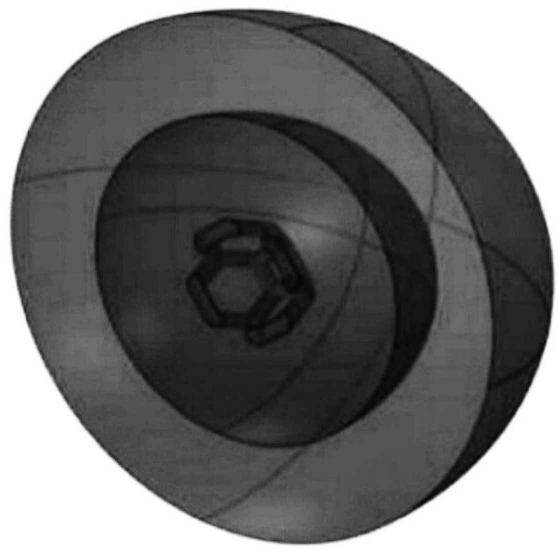

Fig .4. Model geometry TVA simulation with thermo viscous fluid and pressure field.

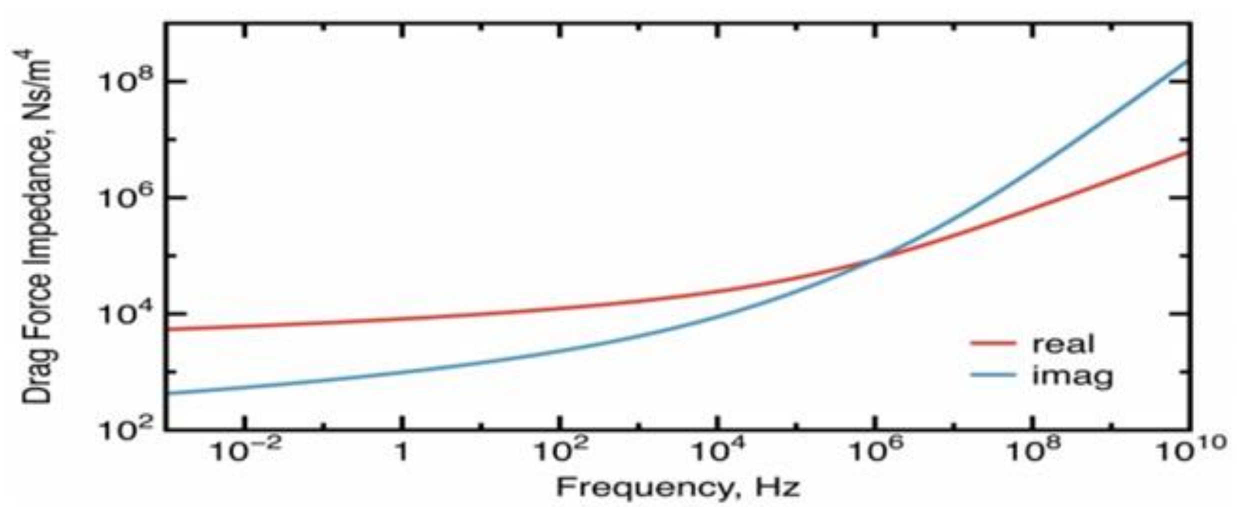

Fig. 5. real and imaginary response of dynamic viscous drag force impedance

2.3.4. Simulation of oscillatory heat transfer effect

The Heat Transfer in Solids and Fluids module within COMSOL Multiphysics has been used to simulate the coupled oscillatory thermal fields within both the solid structure of the foam cell and the surrounding air, over a frequency range of 0.001 Hz – 10 kHz

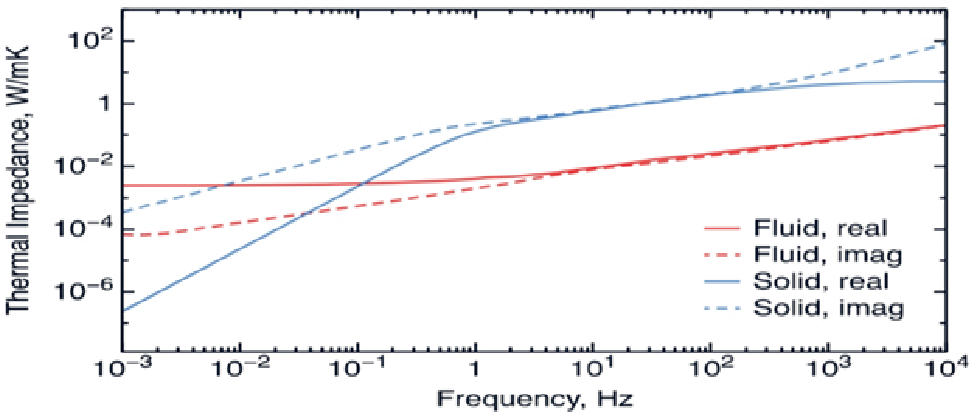

Fig. 6. Real and imaginary parts of fluid and solid thermal impedance.

3.RESULTS AND CONCLUSION

Here used high-fidelity finite element simulations in COMSOL Multiphysics as a controlled "virtual laboratory". At the microscopic level, the approach yields dynamic viscous drag force and oscillatory heat transfer and elasticity matrix with 3D finite element simulations

Successfully developed the cell of melamine foam as a simple isoparametric Kelvin-cell like foam structure. Each cell has a length of 0.283 mm, with the assumed cylindrical struts having a diameter of 5 microns, and a length of 0.100056 mm. Due to the hexagonal geometry of the cell, the oriented struts are assumed to have an off-axis alignment angle of 60 degrees. The cell structure name is tetrakaidecahedron.

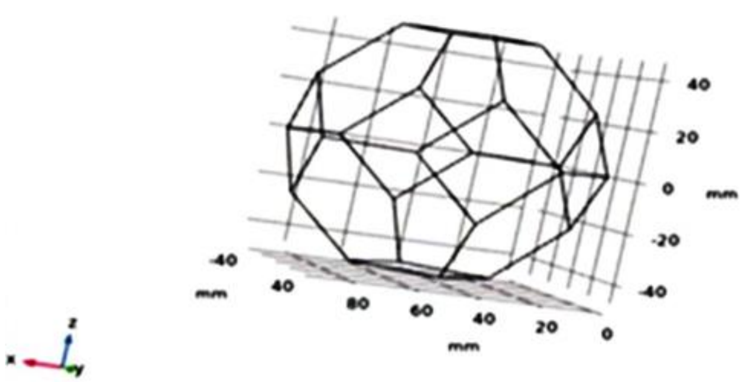

Fig.7. unit cell structure of melamine foam.

Microscopic Cell Elasticity simulation is done with the help of stress-strain relations and Young's modulus and Poisson's ratio can be estimated for input into the stiffness matrix (D) in the stress strain relation equation. The results are get as Young's modulus of 720 kPa, and a Poisson's ratio of 0.4978. In some analytical results shows Young's modulus of 471 kPa and a Poisson's ratio of 0.4992 for the foam cell But they Assume that deformation in the foam cell occurs for strut bending and stretching only, while neglecting torsional behaviour. So can say that Poisson's ratio prediction is comparable with analytical value, while the Young's modulus is 35% greater than the result from the analytical expressions. This difference indicates the potential importance of including the torsional mode in the elasticity analysis of this category of foam cells.

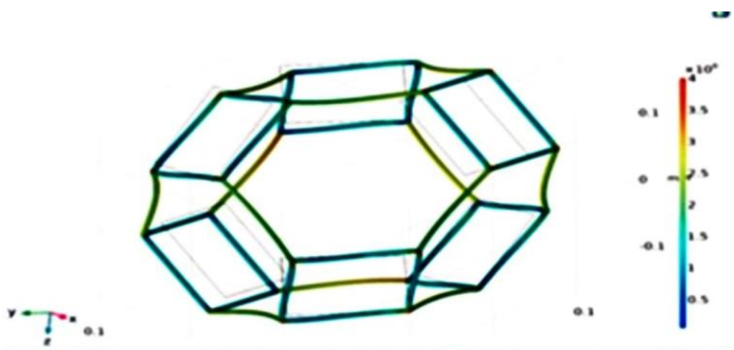

Fig.8 elasticity matrix estimation

The viscous drag losses arising in the interior of a porous material are important for its acoustic performance. Begin with solid and fluid momentum equation. Here, the dynamic viscous drag force estimated from the reference TVA model is 6291 Ns/m^4. Also explored various microstructure configurations (given same strut diameter), as shown below.

Fig.9. longitudinal strut

Fig.10. Transverse struts

a) longitudinal struts, b) transverse struts, c) strut unit cube and d) Melamine foam cell are created and applied the equation for dynamic viscous drag force impedance z. the estimated dynamic viscous drag force impedances for each configuration are: a) 4054 Ns/m4, b) 8108 Ns/m4, c) 6757 Ns/m4 and d) 6291 Ns/m4. Configuration a) has purely longitudinal struts and should be expected to offer the lowest viscous drag forces, while b) is purely transverse and is expected to offer the highest viscous drag forces. The unit cube and Melamine foam cell are comprised of combinations of longitudinal and transverse struts, and thus provide intermediate viscous drag force impedance results.

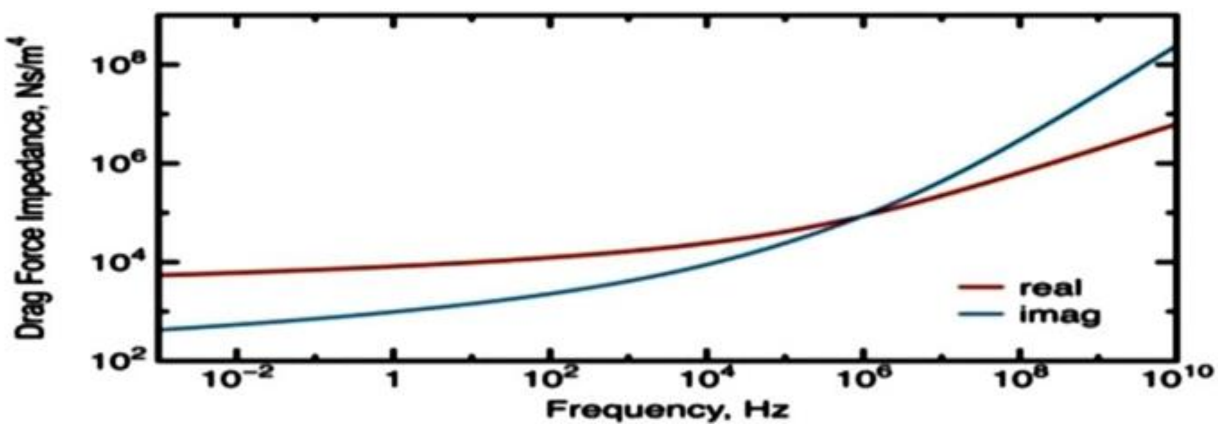

Fig.11. dynamic viscous drag force impedances for real and imaginary part .

For Oscillatory Heat Transfer simulation, the fluid and solid momentum equations, together with a non-equilibrium fluid dilatation equation are needed. Oscillatory heat transfer occurs between the solid phase and the surrounding viscous fluid, resulting in a thermal expansion of the fluid. The Heat Transfer in Solids and Fluids module within COMSOL Multiphysics has been used to simulate the coupled oscillatory thermal fields within the solid structure of the foam cell over a frequency range of 0.001 Hz – 10 kHz.

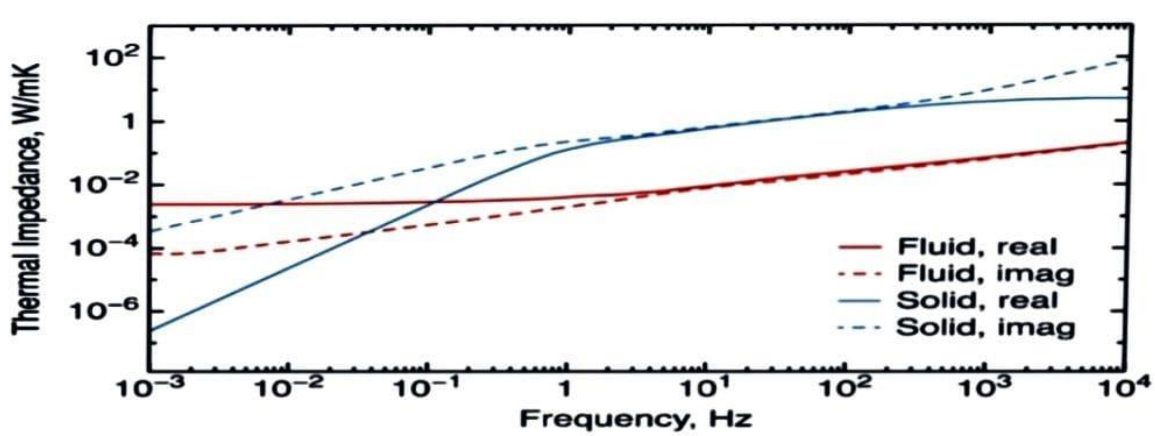

Fig.12. Real and imaginary parts of fluid and solid thermal impedance

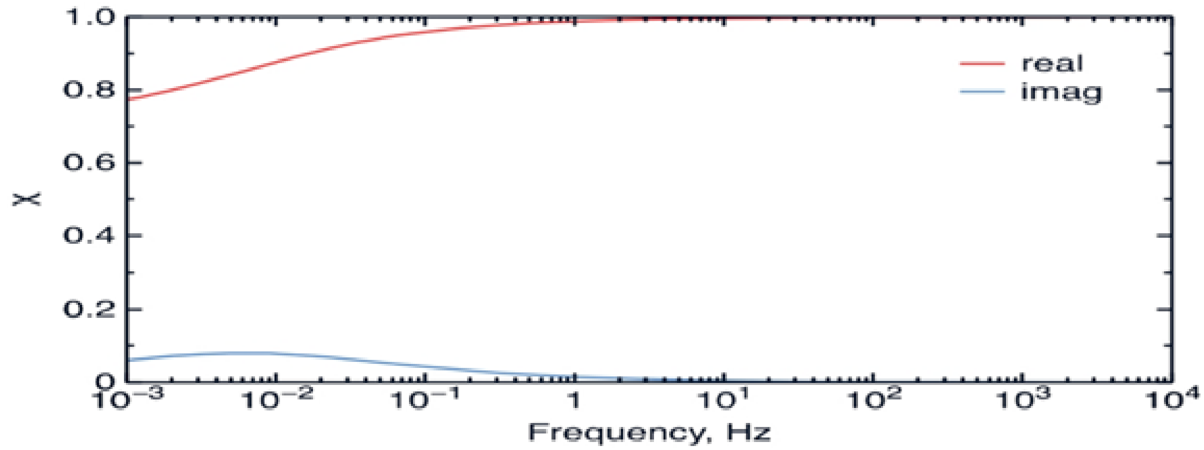

Fig.13. real and imaginary parts of frequency dependent thermal coefficient indicating isothermal to adiabatic thermal behaviour

Fig.17. is indicating a transition from isothermal to adiabatic thermal behaviour at very low frequencies. The approach used here is based on the utilisation of high fidelity finite element simulations to determine the dynamic viscous drag forces, oscillatory heat transfer thermal impedances, elasticity matrices and unit cell formation of melamine porous microstructures.

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