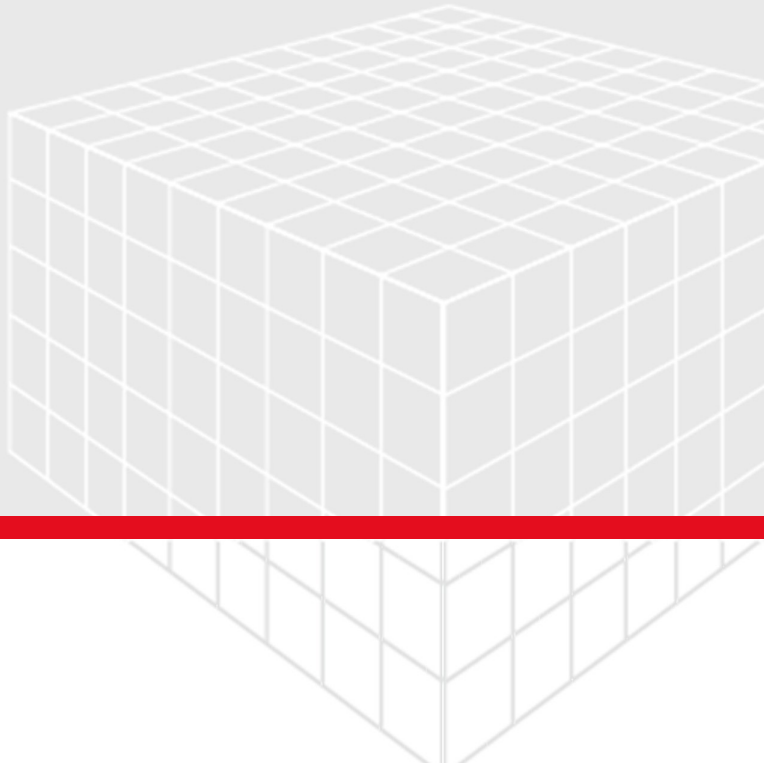
AcoustoDict

User Guide



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AcoustoDict

1 AcoustoDict

Predicting Sound Absorption of the Material

Use AcoustoDict to determine material parameters that allow to predict the sound absorption of the material.

These parameters serve as input data for proven analytical models – the Delany-Bazley model for highly porous materials or the Johnson-Champoux-Allard model for complex pore geometries. Using these models, AcoustoDict quickly calculates the frequency-dependent acoustic absorption curve of the material.

Learn to use AcoustoDict

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Find illustrative application examples on the website.
Our tutorials and seminar videos give you a first hands-on experience. They are collected in the Learning Center.
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1.1 Theoretical Background

The Impedance Tube

In an experimental setup, the acoustic properties of porous absorbers are measured using an impedance tube, commonly referred to as Kundt's tube. Within the impedance tube, a plane sound wave is generated and directed towards a sound-absorbing specimen in front of a reverberant termination. The sound pressure resulting from this is measured by two microphones positioned in front of the material sample. By evaluating the incoming and reflected sound energy at the desired sound frequency values, the sound absorption coefficient of the material is determined.

Topics of Theoretical Background

- Computation of Sound Absorption 4
  Compute the sound adsorption from the characteristic impedance for single- or multilayer materials.
- Determination of the Characteristic Impedance 5
  Compute the characteristic impedance from material parameters with the Delany-Bazley or Johnson-Champoux-Allard model.
- Determination of Material Parameters 8
  Determine the material parameters of the specimen with AcoustoDict.
- Notation 9
  Used variables and symbols are explained here.

1.1.1 Computation of Sound Absorption

The sound absorption coefficient α is computed as

$$\alpha = 1 - |R|^2, \tag{1}$$

where R is the sound pressure reflection coefficient, given by

$$R = \frac{Z_s - Z_0}{Z_s + Z_0} = \frac{Z_s - \rho_0 c_0}{Z_s + \rho_0 c_0}. \tag{2}$$

Here, Z_s is the acoustic surface impedance, ρ_0 is the density of air, c_0 is the speed of sound in air, and $Z_0 = \rho_0 c_0$ is the characteristic impedance of air. The acoustic surface impedance Z_s is a quantity that depends on the sound frequency f, and therefore, the sound pressure reflection coefficient R and the sound absorption coefficient α are quantities that also depend on the sound frequency f. The objective is to calculate the relationship between the sound absorption coefficient α and frequency f for a given porous medium represented as a 3D pore-scale

structure in GeoDict. Refer to Table 2 for a summary of the relevant quantities and their physical units.

The relationship between the acoustic surface impedance Z_s and the properties of the sound-absorbing specimen (porous medium) in the Kundt tube is dependent on whether the porous medium is a single homogeneous layer or if it is composed of multiple layers that are parallel to the sound-reflecting wall.

Single Layer

For a single layer, the acoustic surface impedance Z_s can be derived by

$$Z_s = -jZ_c \cot(k_c d), \tag{3}$$

where d is the thickness of the medium, Z_c is the characteristic impedance, and k_c is the complex wave number. Those three parameters d, Z_c, k_c describe the acoustic properties of the porous layer.

Multilayer

Consider N stacked porous layers with acoustic properties described by i sets of parameters d_i, Z_c, k_c for $i \in \{1,\dots, N\}$, where the layer adjacent to the wall has the index 1. Then, the acoustic surface impedance $Z_{s,i}$ for the stack consisting of layer 1 to i is given by the impedance transmission theorem [Allard and Atalla, Eq 2.16]:

$$Z_{s,1} = -jZ_{c,1} \cot(K_{c,1} d_1), \tag{4}$$

$$Z_{s,i} = Z_{c,i} \frac{Z_{c,i} - jZ_{s,i-1} \cot(k_{c,i} d_i)}{Z_{c,i-1} - jZ_{s,i} \cot(k_{c,i} d_i)} \text{ for } i \in \{2,\dots, N\}, \tag{5}$$

i.e., the acoustic surface impedance for the multilayer is

$$Z_s = Z_{s,N}. \tag{6}$$

The absorption coefficient α and the reflection coefficient R for the multilayer are then computed by (1) and (2), respectively.

1.1.2 Determination of the Characteristic Impedance

With the considerations above, the sound absorption coefficient α of a sound-absorbing specimen in the Kundt tube can be predicted when the characteristic acoustic properties d, Z_c, k_c of each porous layer are known. The thickness d of the medium is a straightforward

quantity, the question then arises regarding how to determine the characteristic impedance and the complex wave number of a porous layer.

These parameters cannot directly be obtained through numerical simulation. Instead, different models exist for various types of porous materials that derive these parameters from other more measurable or computable quantities.

For highly porous absorbers, the Delany–Bazley model can be used and for stiff absorbers, the Johnson–Champoux–Allard model is appropriate.

Delany–Bazley Model

The model of Delany and Bazley[49] is applicable for highly porous materials with porosity close to the maximum of 1. The model expressions for the complex wave number k_c and the characteristic impedance Z_c are functions of frequency [Allard and Atalla, Eq 2.28 and 2.29[49]]:

$$k_c = \frac{\omega}{c_0}\left(1 + 0.0978 \cdot X^{-0.700} - j\,0.1890 \cdot X^{-0.595}\right), \tag{7}$$

$$Z_c = \rho_0 c_0 \left(1 + 0.0571 \cdot X^{-0.754} - j\,0.0870 \cdot X^{-0.732}\right) \tag{8}$$

for $0.01 < X < 1.00$, where the dimensionless parameter X is given by

$$X = \frac{\rho_0 f}{\sigma}. \tag{9}$$

Here, ρ_0 is the air density, c_0 is the sound speed in air, f is the frequency in Hertz, $\omega = 2\pi f$ is the angular frequency, σ is the static air flow resistivity of the porous medium, and j denotes the complex unity. Thus, the only unknown material parameter in this model is the static air flow resistivity σ.

The Delany–Bazley command of AcoustoDict therefore computes the static air flow resistivity σ of porous materials—the only parameter needed to describe the acoustic behavior of highly porous materials. The results predicted by Delany–Bazley are in best agreement with experimental results, even for low frequencies. To achieve continuous dependence of the absorption on the frequency, the correction of Mechel[49] and Miki[49] are used. This modifies the Delany–Bazley formulas to

$$k_c = \frac{\omega}{c_0} \cdot \begin{cases} 1 + 0.0978 \cdot X^{-0.693} - j\,0.1890 \cdot X^{-0.618} & \text{for } X > \frac{1}{60}, \\ -\sqrt{1.466 - j\,0.212 \cdot X^{-1}} & \text{for } X \le \frac{1}{60}, \end{cases} \tag{10}$$

$$Z_c = \rho_0 c_0 \cdot \begin{cases} 1 + 0.0489 \cdot X^{-0.754} - j\,0.0870 \cdot X^{-0.731} & \text{for } X > \frac{1}{60} \\ \frac{0.159 \cdot X^{-1} + j\,1.403}{\sqrt{-1.466 + j\,0.212 \cdot X^{-1}}} & \text{for } X \leq \frac{1}{60} \end{cases} \tag{11}$$

Schladitz et al[49] apply this approach for the acoustic design of nonwoven materials.

Johnson–Champoux–Allard Model

The **Johnson–Champoux–Allard Model** (cf. Allard and Champoux[49], Champoux and Allard[49]) is applicable to porous materials with a rigid frame and arbitrary pore shapes. The model expressions for the complex wave number k_c and the characteristic impedance Z_c are

$$k_c = \omega \sqrt{\frac{\rho_e}{K_e}}, \tag{12}$$

$$Z_c = \sqrt{\rho_e K_e}, \tag{13}$$

where ω is the angular frequency, ρ_e the complex effective density, and K_e the complex dynamic bulk modulus.

The effective density ρ_e is expressed by (cf. [Allard and Champoux, Eq. 13[49]], [Soltani et al, Eq. 18[49]], [Xu and Lin, Eq. 1[49]])

$$\rho_e = \alpha_\infty \rho_0 \left(1 - j \frac{\sigma \phi}{\alpha_\infty \rho_0 \omega} \sqrt{1 + j \frac{4 \alpha_\infty^2 \eta_0 \omega \rho_0}{(\Lambda \sigma \phi)^2}} \right) \tag{14}$$

and the dynamic bulk modulus K_e by

$$K_e = \gamma_0 P_0 \left(\gamma_0 - (\gamma_0 - 1) \left(1 - j \frac{\phi \sigma}{\alpha_\infty \omega \mathrm{Pr}_0 \rho_0} \sqrt{1 + j \frac{4 \alpha_\infty^2 \eta_0 \mathrm{Pr}_0 \omega \rho_0}{(\Lambda \phi \sigma)^2}} \right)^{-1} \right)^{-1} \tag{15}$$

In these equations, the constants η_0 (viscosity), ρ_0 (density), γ_0 (specific heat ratio), Pr_0 (Prandtl number) describe the properties of the ambient air and are given as defined in Table 1[10].

The parameters σ (air flow resistivity), α_∞ (tortuosity), ϕ (porosity), and Λ (viscous characteristic length) describe the properties of the porous material.

1.1.3 Determination of Material Parameters

The Delany–Bazley model and the Johnson–Champoux–Allard model allow to predict the sound absorption of a material if certain material parameters of the porous medium are known.

The only unknown material parameter in the Delany–Bazley model is the static air flow resistivity σ. The Johnson–Champoux–Allard model additionally requires the porosity ϕ, the tortuosity α_∞, and the viscous characteristic length Λ. GeoDict can compute these parameters based on a 3D pore-scale structure of the sound absorbing specimen.

Static air flow resistivity

The static air flow resistivity σ is defined as

$$\sigma = \frac{\eta_0}{\kappa}, \tag{16}$$

where κ is the relative permeability of the porous medium (cf. Table 2 12). The FlowDict section of this User Guide describes in detail how the permeability is computed by solving the Stokes equation.

Tortuosity

The high frequency limit of the tortuosity α_∞ (also called the tortuosity factor) is defined as

$$\alpha_\infty = \frac{\phi}{d^*}, \tag{17}$$

where ϕ is the porosity and d^* the relative diffusivity of the porous medium (Epstein, 1989 49). The DiffuDict section of this User Guide describes in detail how diffusivity and tortuosity are computed by solving the Laplace equation.

The low frequency limit of the tortuosity α_0 is not used in the Johnson–Champoux–Allard equations above, but may serve the user as a reference value, if needed:

$$\alpha_0 = \phi \frac{\int_{V_{\text{pore}}} |v|^2 dx}{\left(\int_{V_{\text{pore}}} v_i dx\right)^2} \tag{18}$$

where v is the air velocity in the pore space V_{pore} and v_i the component of v in through direction.

Viscous characteristic length

The viscous characteristic length Λ is approximated via

$$\Lambda = \sqrt{\frac{8\alpha_0\kappa}{\phi}} \tag{19}$$

with α_0, κ and ϕ as defined above (Johnson, 1987[49]).

Thermal characteristic length

The thermal characteristic length Λ' is the ratio of pore volume to pore surface area:

$$\Lambda' = \frac{2\int_{V_{\text{pore}}} 1}{\int_{\partial V_{\text{pore}}} 1}\,. \tag{20}$$

The pore volume is computed by counting the pore voxels. The pore surface is determined by the method of Ohser and Mücklich[49], see the MatDict section of this User Guide for details. This value is not used in the Johnson–Champoux–Allard equations above, but may serve the user as a reference value, if needed.

1.1.4 Notation

Table 1[10] gives an outline of physical constants and also of quantities that are constant if the environment has constant pressure and temperature. A comprehensive reference for fundamental constants, data, and nomenclature in the field of chemistry and physics is Quack et al[49]. Physical quantities used in AcoustoDict are listed in Table 2[12].

Symbol	Quantity	Value	SI Units	Comment
c_0	speed of sound in air	342.2	$\mathrm{m}\cdot\mathrm{s}^{-1}$	
η_0	dynamic viscosity of	1.825e–5	$\mathrm{Pa}\cdot\mathrm{s}$	$\eta_0 = \rho_0 v_0$

Symbol	Quantity	Value	SI Units	Comment
	air			
P_0	air equilibrium pressure	101325	Pa	
Pr_0	Prandtl number of air	0.702	1	
ρ_0	air density	1.204	$\mathrm{kg} \cdot \mathrm{m}^{-3}$	
T_0	environment temperature	293	K	
γ_0	specific heat ratio of air	1.4	1	

Table 1: Physical constants used in AcoustoDict.

Symbol	Definition	SI Units	Comment
α	sound absorption coefficient	1	
α_∞	high frequency limit of tortuosity (tortuosity factor)	1	
d	thickness of porous medium	m	
f	sound wave frequency	s^{-1}	

Symbol	Definition	SI Units	Comment
K_e	dynamic bulk modulus	Pa	complex
k_c	complex wave number	m^{-1}	complex
κ	permeability	m^2	
Λ	viscous characteristic length	1	
Λ'	thermal characteristic length	1	
ω	angular frequency	s^{-1}	$\omega = 2\pi f$
ϕ	open porosity	1	
P	upscaled pressure at inlet/outlet	Pa	
ρ_e	effective density	$\mathrm{kg} \cdot \mathrm{m}^{-3}$	complex
R	sound pressure reflection coefficient	1	complex
σ	static airflow resistivity	$\mathrm{kg} \cdot \mathrm{m}^{-3} \cdot \mathrm{s}^{-1}$	
X	auxiliary variable	1	$X = \frac{\rho_0 f}{\sigma}$

Symbol	Definition	SI Units	Comment
Z_c	characteristic impedance	$\mathrm{kg} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$	complex
Z_s	acoustic surface impedance	$\mathrm{kg} \cdot \mathrm{m}^{-3} \cdot \mathrm{s}^{-1}$	purely imaginary

Table 2: Physical quantities used in AcoustoDict.

1.2 Delany–Bazley Model

The **Delany-Bazley Model** command determines the porosity and static air flow resistivity of the current 3D structure. These values are then used to predict the sound absorption of the material in a Kundt tube according to the empirical functions[6] derived by Delany and Bazley. The model is valid for highly porous materials with a porosity close to the maximum of 1.

The Delany-Bazley Model command

- Input Parameters[13]
  How to set input parameters in the dialog.
- Results[23]
  How to understand the computational results.
- Data Visualization[25]
  How to visualize the result files.

1.2.1 Input Parameters

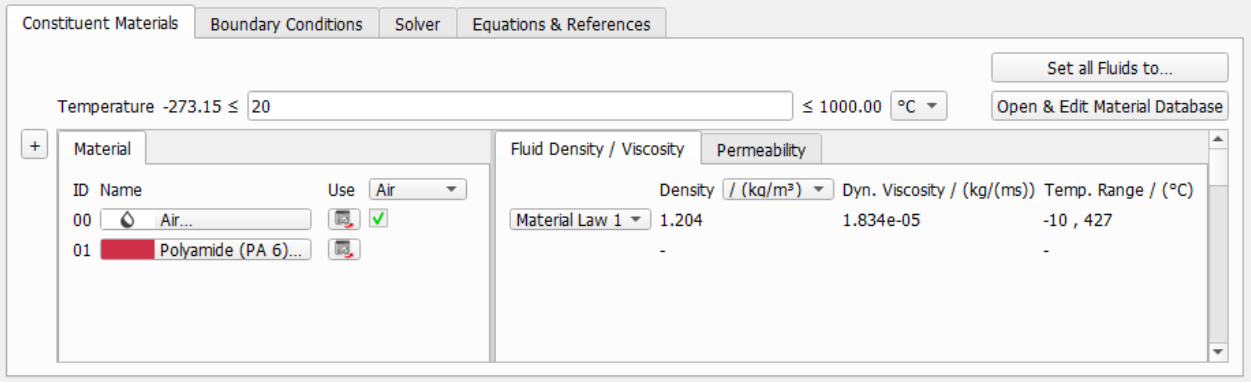
The **AcoustoDict Delany–Bazley Model** dialog opens when clicking the **Options**' **Edit...** button in the AcoustoDict section. The parameters necessary to run the solver can be entered under the **Constituent Materials**, **Boundary Conditions**, and **Solver** tabs. The **Equations and References** tab displays further information about the model.

Click **OK** to confirm the entered solver options, or click **Cancel** to close the dialog without modifications.

The **Result File Name (*.gdr)** of the AcoustoDict simulation must be entered in the edit box. Choose a name according to your current project. The results files are saved in the chosen project folder (**File → Choose Project Folder**, in the menu bar).

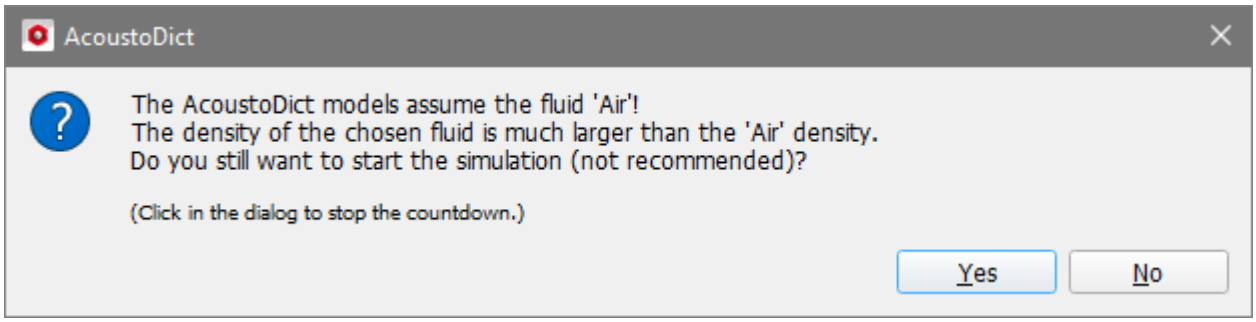
Constituent Materials

Under the **Constituent Materials** tab, the constituent materials of the fluid phase and the solid phase in the structure model currently in memory are shown.



The Delany–Bazley model is only valid when the fluid is air and the simulations assume that this is the case. If the constituent material for the fluid occupying the pore space is changed to

some other constituent material (which is possible to do), a warning pops up when trying to run the simulation.

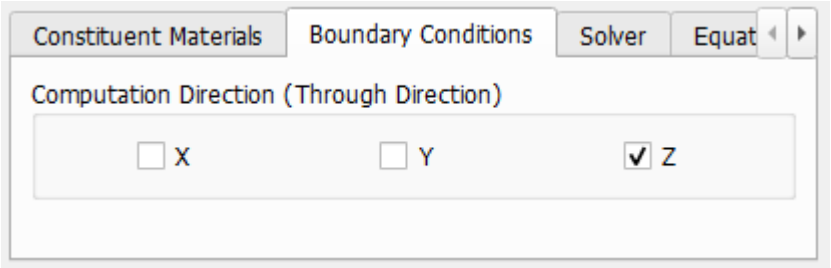


Click **No** and go back to the Constituent Materials tab. Click on the button for Material ID 00 to change it to Air through the **Material Selector**.

Under the assumptions made in the Delany–Bazley model, only the air flow resistivity and the porosity of the material are important for the acoustic absorption. Thus, the constituent materials chosen for the solid phase do not influence the results.

Boundary Conditions

In the **Computation Directions** panel of the **Boundary Conditions** tab, choose the direction of wave propagation (also referred to as **Through Direction**). Only one through direction can be active.



Solver

AcoustoDict solves the Stokes equation to compute the air flow resistivity σ. Select which of the two solvers **EJ** or **LIR** is used to solve the Stokes problem. For highly porous structures, the LIR solver is in general recommended.

For both solvers, set the **Simulation Stopping Criterion**, the solver **Parallelization**, and decide if the solver output files should be discarded. For the LIR solver, expand the dialog to show also the **Advanced Options** if required.

Simulation Stopping Criterion

The equations are solved by an iterative approach.

Iterative Solver

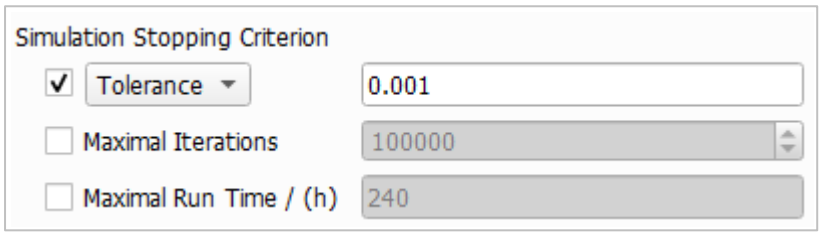
The basic idea of an iterative method is to

1. Start with some initial guess for the unknown values
2. Improve the current values in each iterative step
3. Repeat the iterative process until one of the stopping criteria is reached.

The iterative process is controlled by setting the values and activation for **Tolerance, Residual, Error Bound**, **Maximal Iterations**, and **Maximal Run Time (h**). The stopping criteria apply for each computational direction individually.

If multiple stopping criteria are selected, the first criterion that is reached causes the solver to stop.

The stopping criterion that has been reached can be viewed in the Result Viewer of the GeoDict result file (*.gdr) under the **Results Report** tab.



The **Tolerance** stopping criterion looks for stagnation of the method when the process becomes stationary, i.e., the improvement in the permeability value becomes extremely small from iteration to iteration.

In each iteration, the solver checks for the current computed value x_c against the values x_{c-i} of the last 100 iterations if there are any changes.

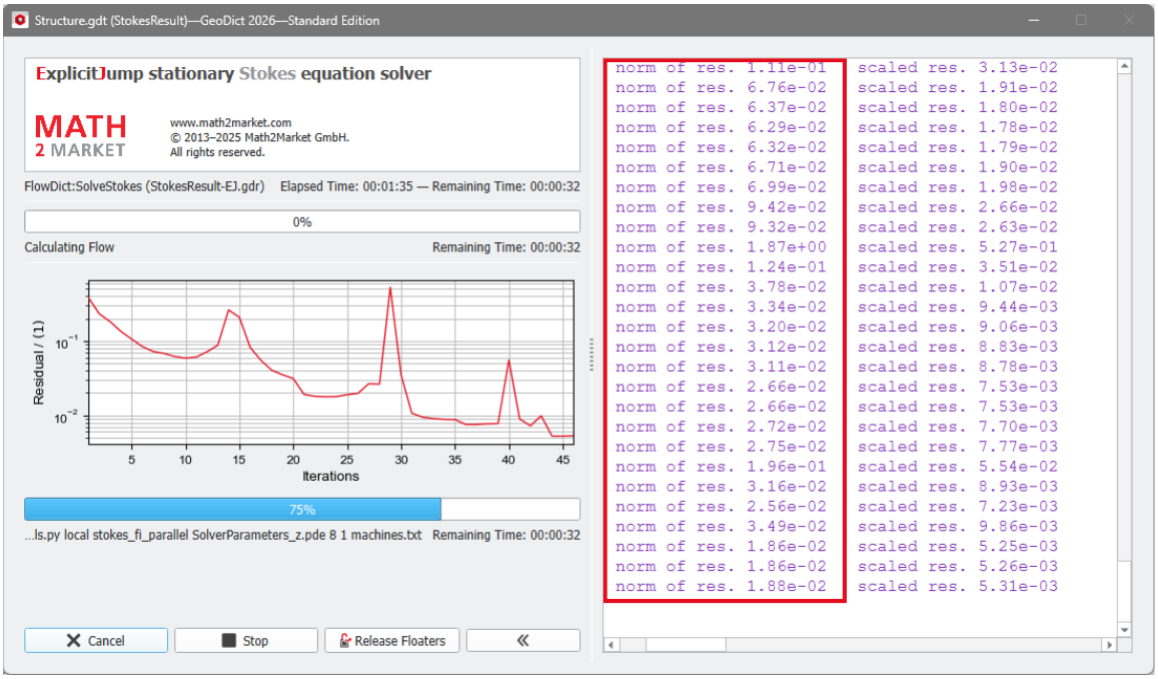
$$\max_{i\in[1,100]} \frac{x_c - x_{c-i}}{x_{c-i}} < \text{tolerance} \tag{21}$$

The computation is stopped if the maximal relative change is smaller than the value entered for **Tolerance**. When there is doubt about the quality of the solution, decrease the **Tolerance** value by a factor of ten. The drawback of this criterion is that the solver sometimes might stop too early in case of slow convergence rate or at local extrema of oscillatory convergence curves.

When the **Residual** stopping criterion is used, the iteration is stopped if the solution satisfies the equation up to the required accuracy.

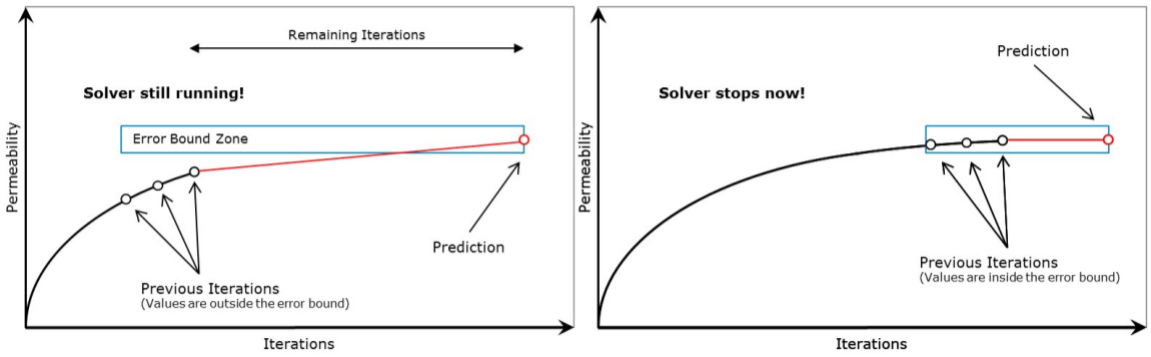
By setting the stopping criterion to **Residual**, the computations terminate as soon as

the relative norm drops below the selected residual threshold. The relative norm of the Schur Complement residual is computed and displayed in the console window during the calculations. The console is visible by clicking the double arrow button on the lower right corner in the progress dialog.



The recommendation to choose **Tolerance** or **Residual** for the **EJ** solver is based on the structure's porosity. Both give similar results for highly porous structures. For dense structures, if using the Schur Complement **Residual**, the relative norm of the residual may be small even though the correct permeability has not been reached. So, when in doubt, use the **Tolerance** criteria – the default option.

The stopping criterion **Error Bound** uses the result of previous iterations, and predicts the final solution based on linear and quadratic extrapolation. The solver stops if the relative difference between computed and predicted solution is smaller than the specified error bound. The stopping criterion recognizes oscillations in the convergence behavior and prevents premature stopping at local minima or maxima. A damped convergence curve is fit through the oscillating curve and the solver stops then regarding the damped convergence curve.



If the Krylov method (under LIR - Advanced Options) is activated, the definition of **Error Bound** is somewhat different. Here, no prediction is made, instead the continuity between neighboring cells and the conservation of mass is checked. The maximal value is normalized by the mean flow and if this value is smaller than the **Error Bound** the simulation stops.

Use the **Maximum Iterations** value or the **Maximum Run Time (h)** stopping criteria causes the solver to stop if the maximal number of iterations and/or the maximal runtime (in hours) is exceeded.

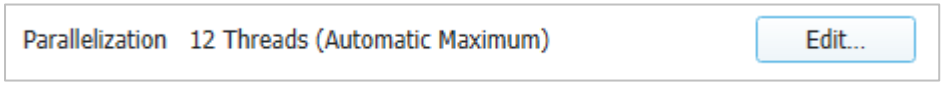
When the solver stops because one of these criteria has been reached, no guarantee on the quality of solution can be given. In this case, a warning is printed into the report. The following possibilities might help:

- Check the corresponding .log file to see how large the residual values and the permeability values are. If the permeability values are in reasonable range and they do not have changed during the last iterations, you may decide to use the current result.
- Double-check the structure and parameter values. Unphysical parameters or too rough resolution of the structure (leading, e.g., to artificial unconnected components) can cause an iterative solver to fail.

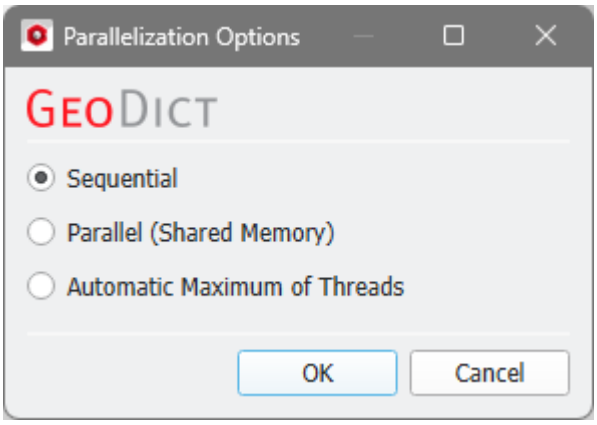
Parallelization

Control how many threads are used for the computation. Parallelization is possible if your license and hardware allow it.

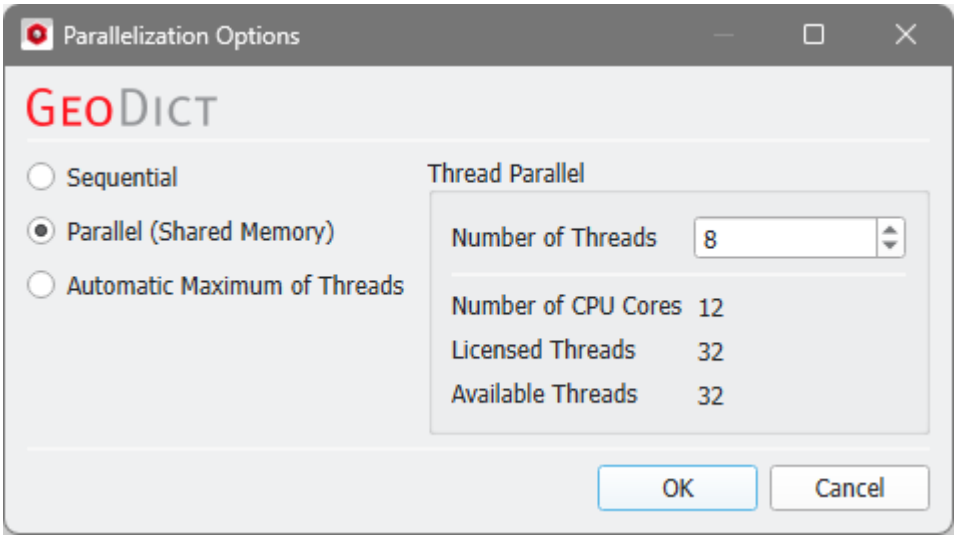
The **Parallelization Options** dialog opens when clicking the **Edit** button and you can choose between **Sequential**, **Parallel (Shared Memory)**, or **Automatic Maximum of Threads**.



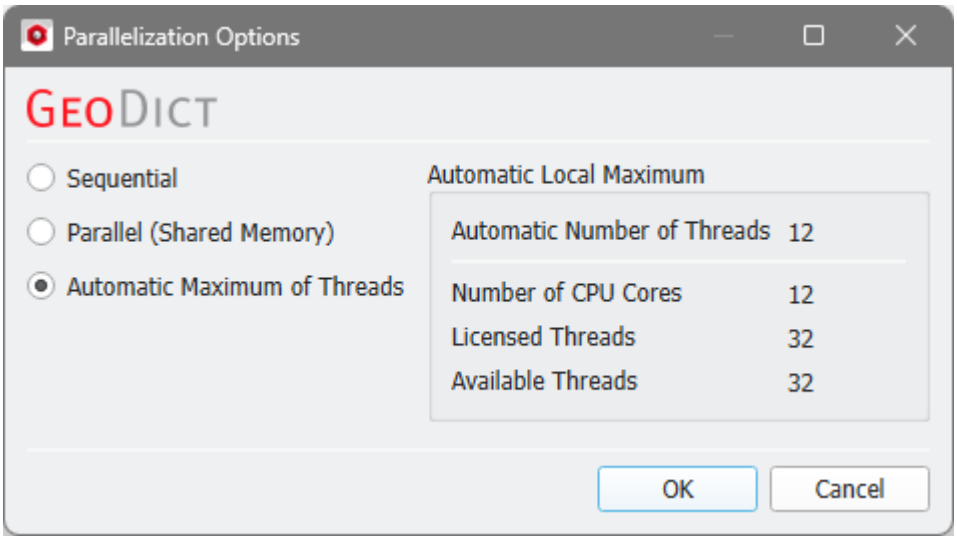
Selecting **Sequential** will not apply parallelization and only one thread is used for the computation.



When **Parallel (Shared Memory)** is selected, the **Number of Threads** can be entered. Below, the **Number of CPU Cores** that the current machine has, the maximum number of **Licensed Threads** and the number of those licensed threads that are available (**Available Threads**) are shown in the dialog. Of course, the maximal number of parallel processes you can use, is the smallest of those three numbers.



If **Automatic Maximum of Threads** is selected, the number of parallel processes is automatically selected for optimal speed, based on the CPU cores and licensed parallel processes.

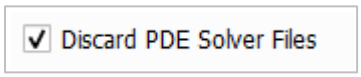


The **Automatic Local Maximum** of processes is automatically selected, which is the minimum of **Number of CPU Cores**, **Licensed Threads**, and **Available Threads**.

For more details on how to set up and run parallel computations, consult the High Performance Computing chapter.

Discard PDE Solver Files

Checking **Discard PDE Solver Files** causes the deletion of all intermediate computation files, such as log files and flow field files.



Only the content of the final GeoDict result file (*.gdr) is stored.

While having the benefit of saving hard disk storage place, discarding intermediate solver files has also the effect of disabling the 3D visualization of the results.

Advanced Options (LIR): Write Compressed Volume Fields

The LIR solver uses a very memory efficient adaptive grid structure for the simulations.

If the option **Write Compressed Volume Fields** is checked, then the adaptive grid is used as compression method for writing out *.vap files. This option allows to save 80-90% space on hard drive. The runtime for writing *.vap files is also reduced significantly. But the runtime for loading and uncompressing of compressed *.vap is increased by the amount of runtime that was saved for writing out compressed *.vap files.

If the option **Write Compressed Volume Fields** is not checked, then a usual regular grid is used for writing out *.vap files.

Advanced Options (LIR): Optimization Options

The **Multigrid Method** (see, e.g., Wesseling, 2004) was introduced to speed-up the computation and reduce the runtime significantly. The main idea of **Multigrid** is the usage of multiple coarser adaptive grids to speed up convergence behavior but requires only little more memory.

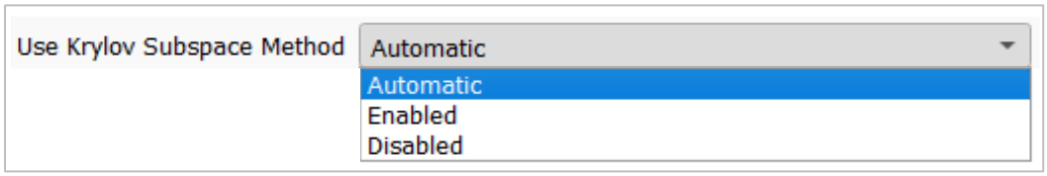
The method is available to solve the Stokes and Stokes–Brinkman equations as well as for solving mechanics, diffusion, thermal, and electrical conduction and is enabled by default.

Another speed-up option to accelerate the convergence behavior of the LIR solver is called **Krylov Subspace Method**.

The runtime of the LIR solver depends on many different properties of the structure and the simulation parameters. The BiCGStab algorithm is used, which can reduce the runtime for challenging simulation very drastically.

Note! Using the BiCGStab method approximately doubles the amount of RAM needed for the computation.

Unfortunately, the Krylov method is not always faster than a simulation without the Krylov method and therefore we introduced an **Automatic** mode which uses some heuristics to choose the most efficient method based on structure, material parameters, and boundary conditions automatically. Of course, it is possible to explicitly enable (**Enabled**) or disable (**Disabled**) the method.

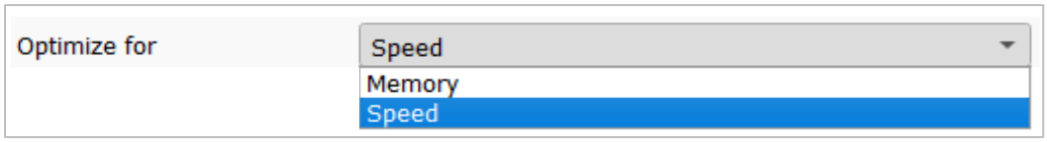


Note! In case that the Krylov subspace method (BICGStab) is used, the **Relaxation** may also be adapted automatically.

Depending on the material parameters and geometry of the structure, the underlying mathematical problem can vary in complexity, thus influencing the behavior of the solver. The more complex the problem is, the more stable the solver settings should be.

With the **Relaxation** number, the solver is adjusted from **Stable** (which results in higher number of iterations, slower time stepping, and longer solver run times), to **Fast**, which makes the solver run less iterations but implies the risk that the solver does not converge. The **Relaxation** is a parameter of the SOR method and must be between 0 and 2 to ensure convergence. For relaxation values smaller than one (<1.0), the simulation is more stable. For relaxation values larger than one (>1.0), the simulation converges faster.

The **LIR** solver can **Optimize for Speed** or **Memory**.



- If **Speed** is chosen, the solver constructs additional optimization structures. The runtime is decreased by up to 30% but requires up to 50% more memory compared to the other option.
- If **Memory** is chosen, the runtime is increased by up to 40% but the solver requires up to 50% less memory.

Advanced Options (LIR): Grid Options

The **Grid Type** decides what kind of tree structure is used for the simulation.

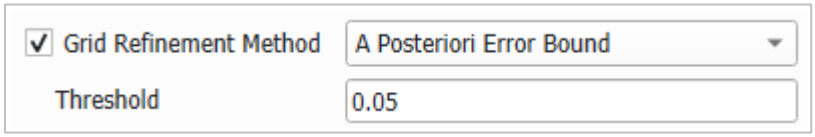
The default option is **LIR-Tree** and should always be used. The solver uses an adaptive grid structure called LIR-tree and needs up to 10 times less runtime and memory compared to the **Regular Grid** option.

The solver can analyze the result field during the computation and improves the adaptive grid in places where more accuracy is needed. The LIR solver splits cells where a high gradient occurs.

The solver can analyze the computed field and refines the adaptive grid during the computation at locations where more accuracy is needed. The LIR solver splits cells where a high gradients occur when the **Grid Refinement Method** is enabled. In this case, the additional parameters **Number of Grid Refinements**, **Allow Sub-Voxel Resolution**, and **Allow Grid Re-Coarsening** become available.

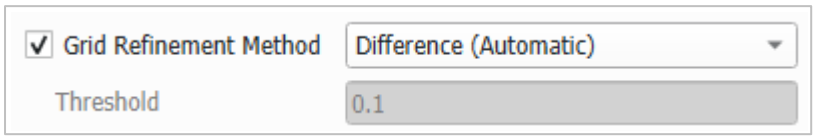
Select one of the three available refinement methods from the drop-down menu.

When **A Posteriori Error Bound** is selected, the solver targets the specified accuracy **Threshold**. While the **Error Bound** (set as Simulation Stopping Criterion) determines the relative error in the solution of the linear system, **A Posteriori Error Bound** refers to the relative error estimated by comparing high-order and low-order discrete solutions. The accuracy **Threshold** refers to the relative error to the analytical solution and the value must be between 0.0 and 1.0.

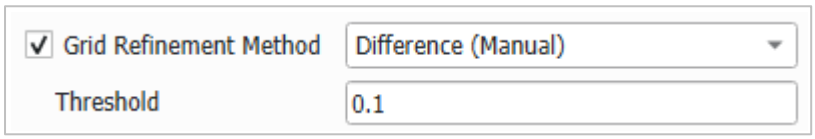


Choosing **Difference (Automatic)** leads to computational cells being split when the

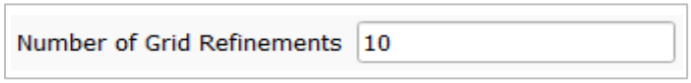
difference in values between neighboring cells exceeds a certain **Threshold**. The solver automatically chooses all internal parameters based on the structure and simulation settings. For this option, cells are split where the current gradient is greater than the **Threshold** multiplied by the maximum gradient, where the threshold is determined automatically.



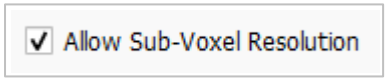
Selecting **Difference (Manual)** also causes the computational cells to be split when the difference in values between neighboring cells exceeds the specified **Threshold**. You can specify all parameters (Threshold and Number of Grid Refinements) for the grid refinement manually. For this option, cells are split where the current gradient is greater than the **Threshold** multiplied by the maximum gradient. The **Threshold** value must be between 0.0 and 1.0. The recommended value range is between 0.05 and 0.1.



The **Number of Grid Refinements** controls the maximum number of grid refinements that the solver can perform during the simulation. The value should be set between 0 and 10, where a value of 0 means that no grid refinements will be made. Grid refinements may increase the number of iterations, runtime, and memory requirements.



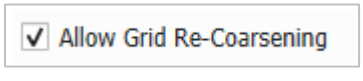
When **Allow Sub-Voxel Resolution** is enabled, the solver is allowed to split computational cells to sizes smaller than the voxel length.



This feature is beneficial for low-porosity structures for which the pore throats require finer resolution.

Enabling this feature may increase the number of iterations, runtime, and memory requirements.

Check **Allow Grid Re-Coarsening** to allow the solver to automatically revert the grid refinement and coarsen the computational cells.



This means, grid refinement is done temporarily. Afterwards, the cells are merged as soon as accuracy is not needed anymore. This reduces the memory and runtime requirements.

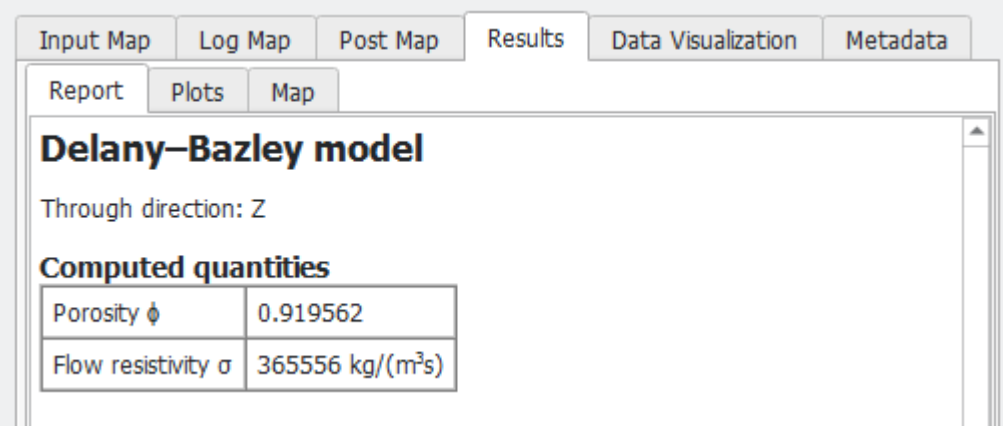
Equations and References

This tab displays formulas and references which are explained in more detail in the Theoretical Background[4].

1.2.2 Results

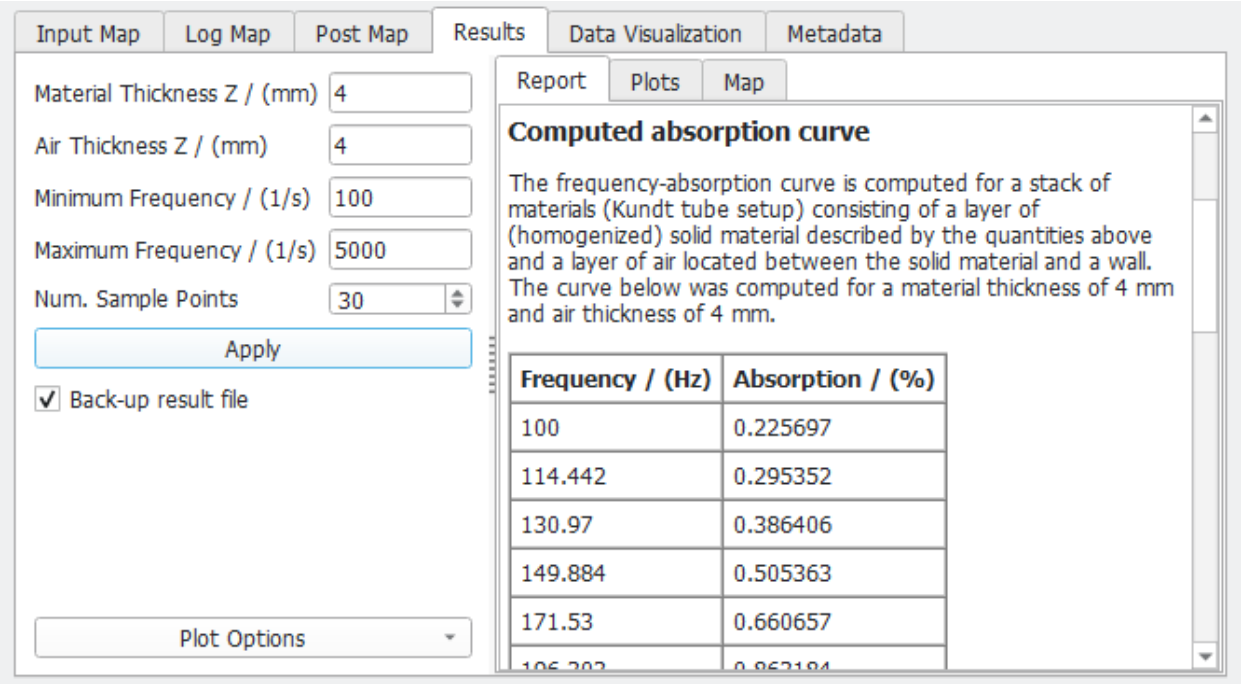
Click **OK** to input the entered parameters, and then click **Run** in the AcoustoDict section to start the command.

The results are immediately shown in the opening Result Viewer after the process is finished, the screenshot below shows the calculated acoustic parameter values for the Delany–Bazley model. The tab shows porosity and flow resistivity calculated in the direction of interest. The porosity value must be close to 1.0 (or over 90%), indicating a highly porous structure and the Delany–Bazley model is (indeed) applicable.

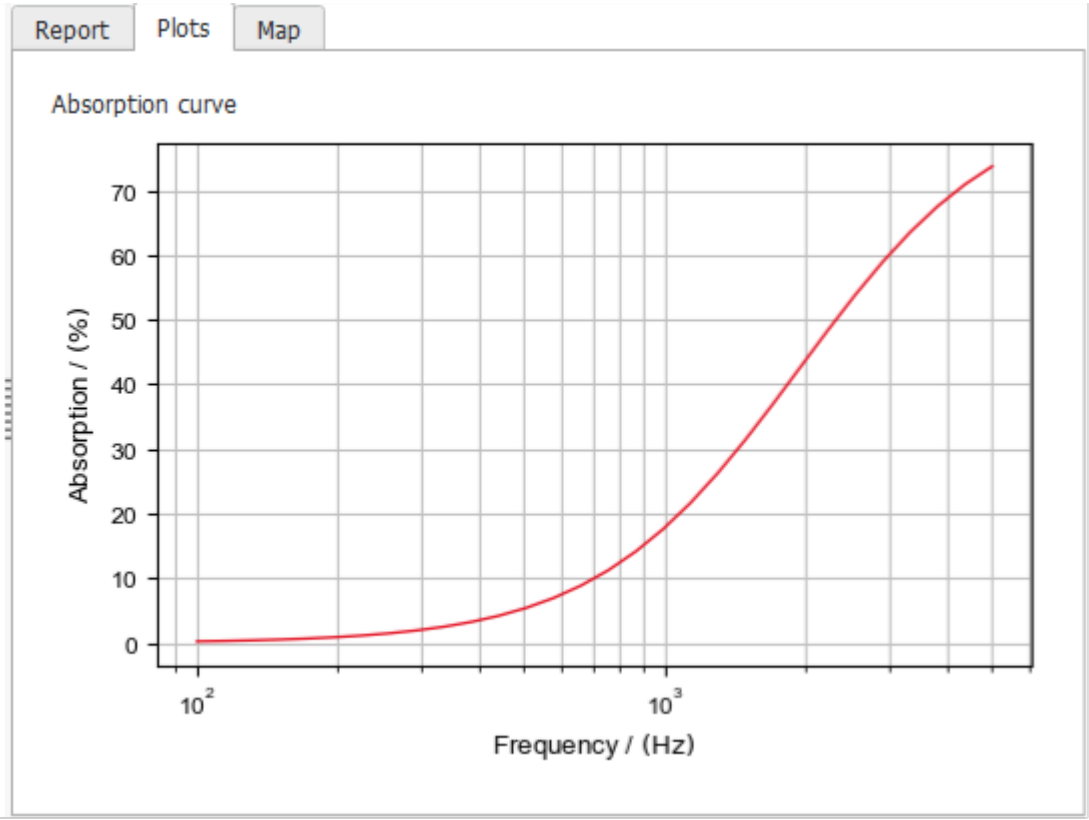


Absorption curve

The frequency–absorption curve is computed for a stack of materials in the Kundt tube setup, consisting of a layer of (homogenized) solid material described by the computed flow resistivity and porosity and a layer of air located between the solid material and a wall. The thickness of the material and the air layer can be set in the panel on the left, as **Material Thickness Z** and **Air Thickness Z**. By default, 4 mm are used for both values.



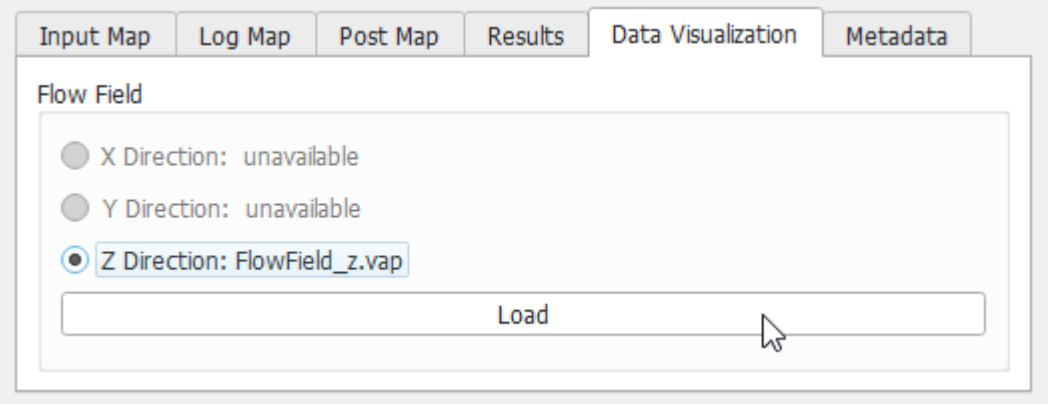
The absorption is computed in a range given by the **Minimum Frequency** and **Maximum Frequency** values, using the entered number of **Sample Points**. The curve is shown in the **Results→Plots** subtab.



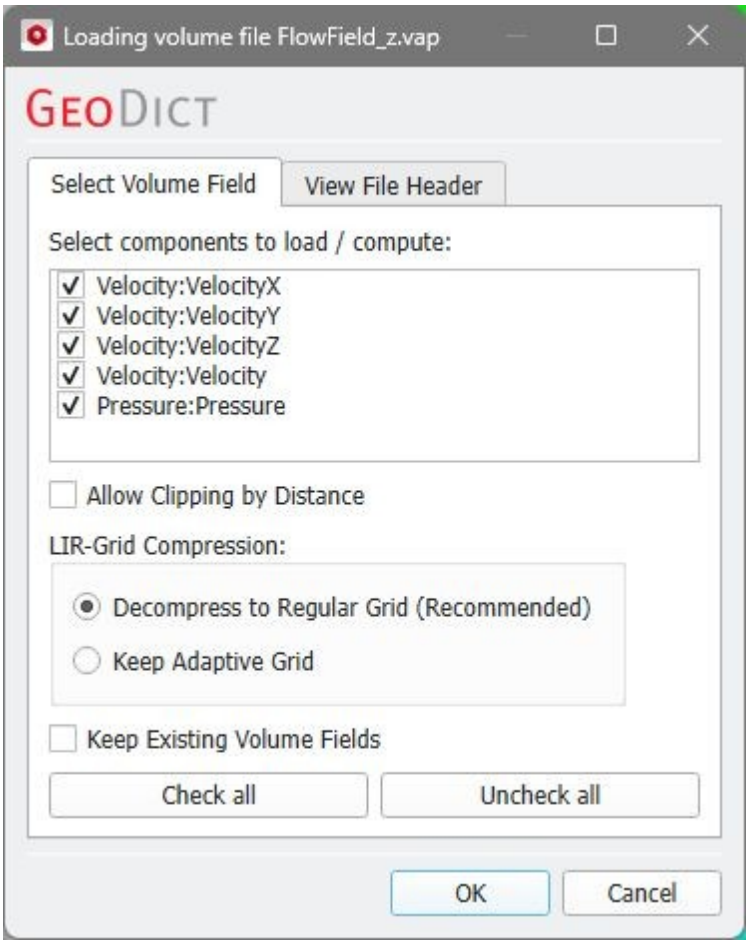
The **Results Map** subtab gives access to the media-dependent acoustic parameters values computed for the selected acoustic model.

1.2.3 Data Visualization

Under the **Data Visualization** tab, the results can be loaded for graphical visualization in 2D-Cross section view or 3D-Rendering. Flow fields that have been calculated to determine the flow resistivity values can be visualized by clicking **Load**.



In the opening **Loading volume file** dialog, select the volume fields you want to load. Supplemental fields, as, e.g., the Velocity:Velocity field shown in the dialog, will be computed from the saved fields in the file.



Selecting **Allow Clipping by Distance** also computes a distance field using a signed Euclidean distance transform (see the MatDict-EDT chapter for more information). The distances can

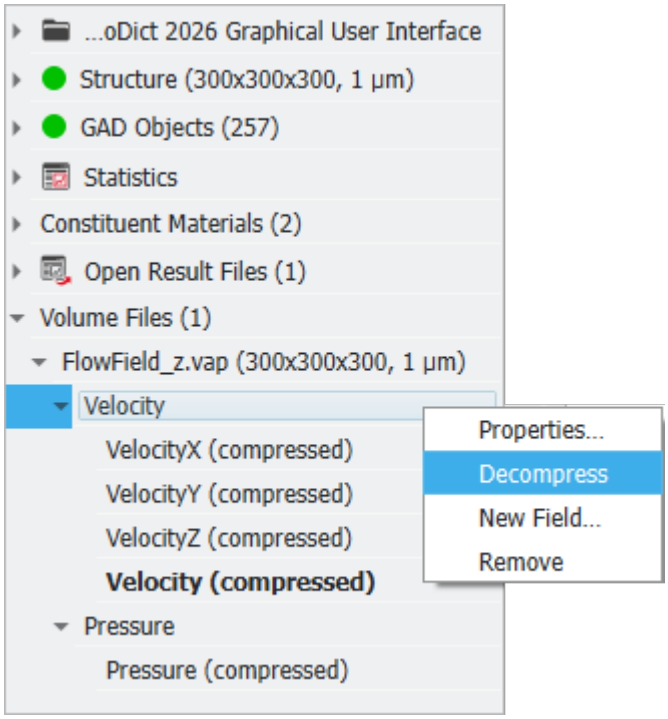
then be used to threshold the other loaded volume fields.

A compressed field is saved when checking **Write Compressed Volume Fields** under the Solver tab of the **LIR Solver Options** dialog. If a compressed volume field is opened, it is possible to choose either **Decompress to Regular Grid** (which is the recommended option) or **Keep Adaptive Grid**, which means to load the field in compressed form.

Important! Some visualization features of volume fields (e.g the visualization of streamlines) are available only if the field is loaded in decompressed form.

However, loading a compressed volume field needs less memory, which can be advantageous for large structures.

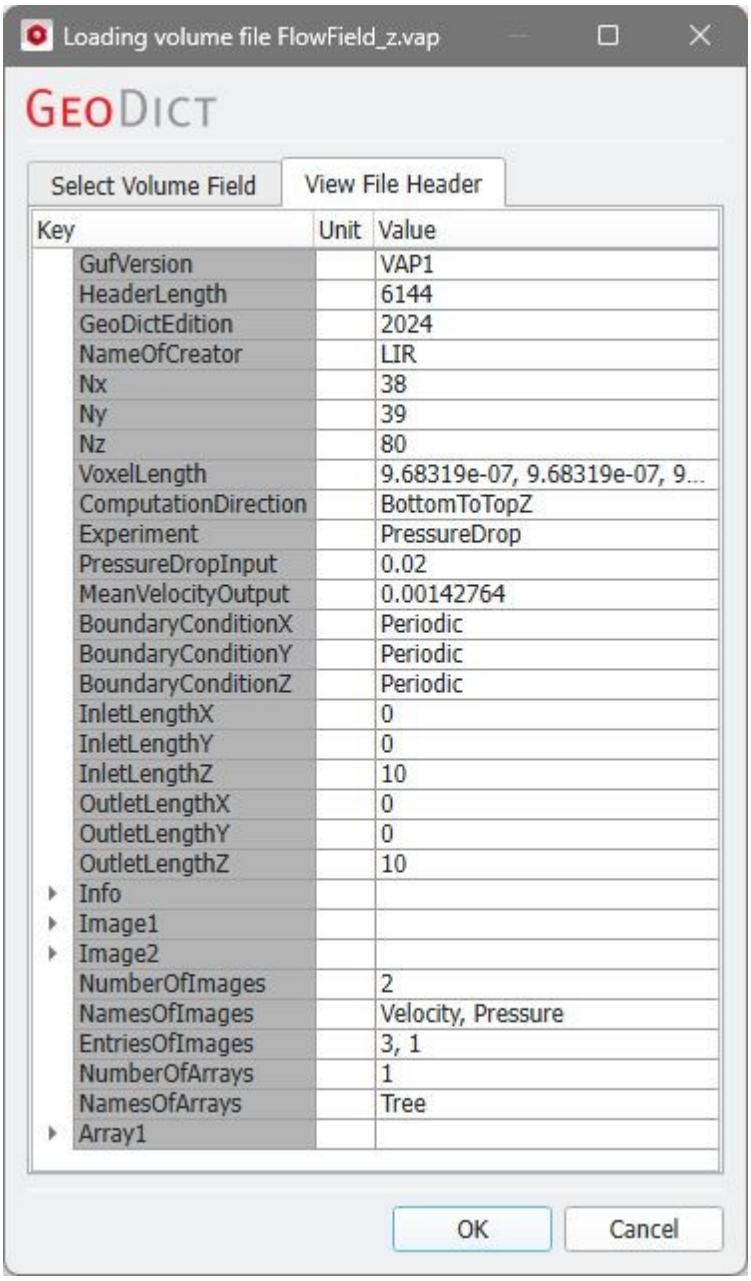
It is also possible to load a volume file in compressed form and decompress it later. In the project status section on the left, right click on the volume image and choose **Decompress**.



Check **Keep existing Volume Fields**, if already loaded volume fields should be kept in the GeoDict memory.

With the buttons **Check all** and **Uncheck all**, the fields from the volume file you want to load can be selected or deselected at once.

In the **View File Header** tab you can see the header of the volume file. The header provides information about the domain size, voxel length, boundary conditions, and many more. Nothing can be edited in this tab, only the available information, depending on the volume file type, is shown.



Know how! You can open a volume file with a text editor to read the header which is the only human-readable part. However, it is more convenient to view this during import in GeoDict. Moreover, large volume files take a long time to open in a text editor, or the editor may be unable to open them at all.

Find more about the content of the header in volume files in the GeoPy Scripting chapter.

Clicking **OK** starts the import of the volume file.

The options for the visualization of flow results are explained in detail in the Visualization chapter.

1.3 Johnson–Champoux–Allard Model

The **Johnson-Champoux-Allard Model** command determines the static air flow resistivity, the tortuosity, the viscous characteristic length and the thermal characteristic length of the current 3D structure. These values are then used to predict the sound absorption of the material in a Kundt tube according to the empirical functions[7] derived by Johnson, Champoux and Allard (cf. Allard and Champoux[49], Champoux and Allard[49]). The model is valid for porous materials with a rigid frame and arbitrary pore shapes.

The Johnson-Champoux-Allard Model command

- Input Parameters[28]
  How to set input parameters in the dialog.
- Results[33]
  How to understand the computational results.
- Data Visualization[35]
  How to visualize the result files.

1.3.1 Input Parameters

The **AcoustoDict Johnson–Champoux–Allard Model Options** dialog opens when clicking the **Options**' **Edit...** button in the **AcoustoDict** section.

The options necessary to run the solvers can be entered under the **Constituent Materials**, **Boundary Conditions**, **Flow Solver**, and **Diffusion Solver** tabs. The command internally has to solve two partial differential equations:

- The Stokes equations to compute the air flow resistivity,
- The Laplace equation to determine the tortuosity.

The **Equations and References** tab displays further information about the model.

Constituent Materials

Under the **Constituent Materials** tab, all parameters are as described for the Delany–Bazley model[13]. The Allard–Johnson model also assumes that the fluid in the pore space is air and it should be set that way.

Boundary Conditions

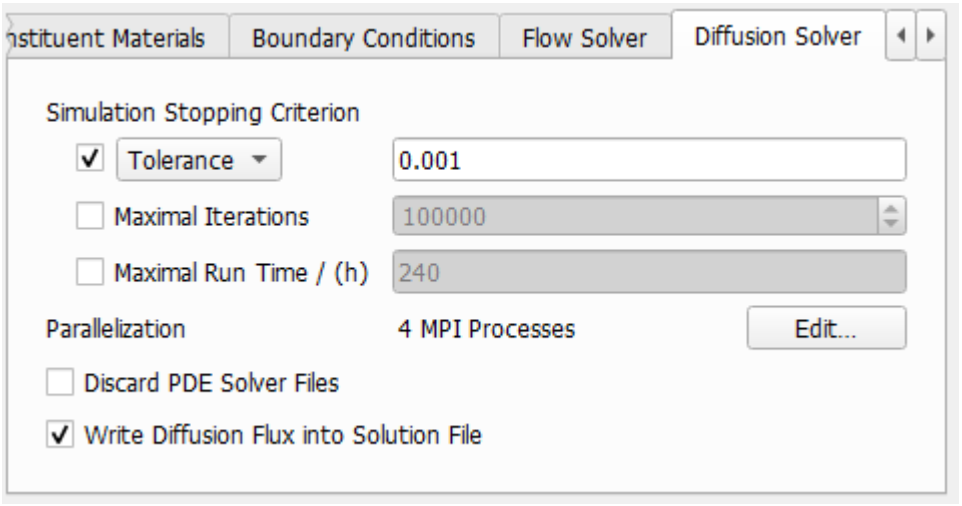
For the **Boundary Conditions**, the options are the same as for the Delany–Bazley model[14].

Flow Solver

The parameters entered under the **Flow Solver** tab have the same meaning as described for the Delany–Bazley model[14].

Diffusion Solver

AcoustoDict solves the Laplace equation to compute tortuosity, diffusivity, and viscous characteristic length. For this, the **EJ** solver is used.



Simulation Stopping Criterion

The equations are solved by an iterative approach.

Iterative Solver

The basic idea of an iterative method is to

1. Start with some initial guess for the unknown values
2. Improve the current values in each iterative step
3. Repeat the iterative process until one of the stopping criteria is reached.

The iterative process is controlled by setting the values and activation for **Tolerance, Residual**, **Maximal Iterations**, and **Maximal Run Time (h**). The stopping criteria apply for each computational direction individually.

If multiple stopping criteria are selected, the first criterion that is reached causes the solver to stop.

The **Tolerance** stopping criterion looks for stagnation of the method when the process becomes stationary, i.e., the improvement in the permeability value becomes extremely small from iteration to iteration.

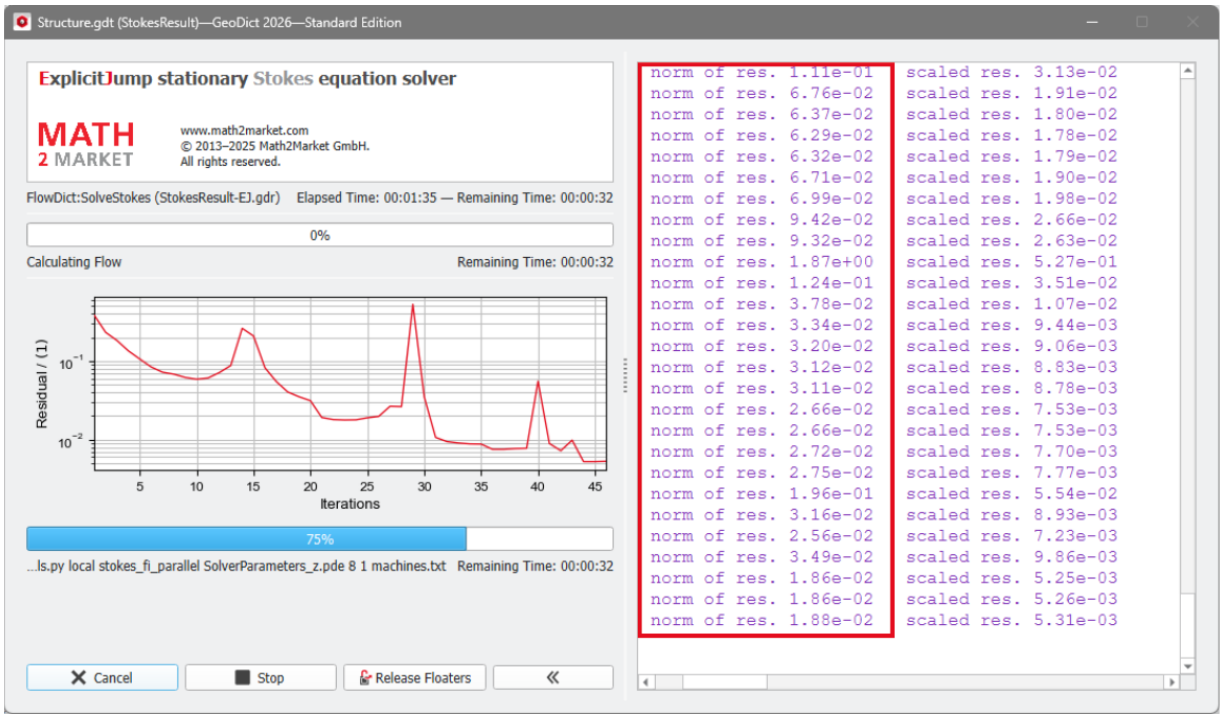
In each iteration, the solver checks for the current computed value x_c against the values x_{c-i} of the last 100 iterations if there are any changes.

$$\max_{i\in[1,100]} \frac{x_c - x_{c-i}}{x_{c-i}} < \text{tolerance} \tag{22}$$

The computation is stopped if the maximal relative change is smaller than the value entered for **Tolerance**. When there is doubt about the quality of the solution, decrease the **Tolerance** value by a factor of ten. The drawback of this criterion is that the solver sometimes might stop too early in case of slow convergence rate or at local extrema of oscillatory convergence curves.

When the **Residual** stopping criterion is used, the iteration is stopped if the solution satisfies the equation up to the required accuracy.

By setting the stopping criterion to **Residual**, the computations terminate as soon as the relative norm drops below the selected residual threshold. The relative norm of the Schur Complement residual is computed and displayed in the console window during the calculations. The console is visible by clicking the double arrow button on the lower right corner in the progress dialog.



The recommendation to choose **Tolerance** or **Residual** for the **EJ** solver is based on the structure's porosity. Both give similar results for highly porous structures. For dense structures, if using the Schur Complement **Residual**, the relative norm of the residual may be small even though the correct permeability has not been reached. So, when in doubt, use the **Tolerance** criteria – the default option.

Use the **Maximum Iterations** value or the **Maximum Run Time (h)** stopping criteria causes the solver to stop if the maximal number of iterations and/or the maximal runtime (in hours) is exceeded.

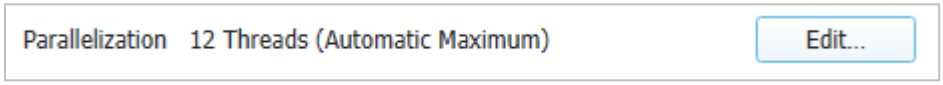
When the solver stops because one of these criteria has been reached, no guarantee on the quality of solution can be given. In this case, a warning is printed into the report. The following possibilities might help:

- Check the corresponding .log file to see how large the residual values and the permeability values are. If the permeability values are in reasonable range and they do not have changed during the last iterations, you may decide to use the current result.
- Double-check the structure and parameter values. Unphysical parameters or too rough resolution of the structure (leading, e.g., to artificial unconnected components) can cause an iterative solver to fail.

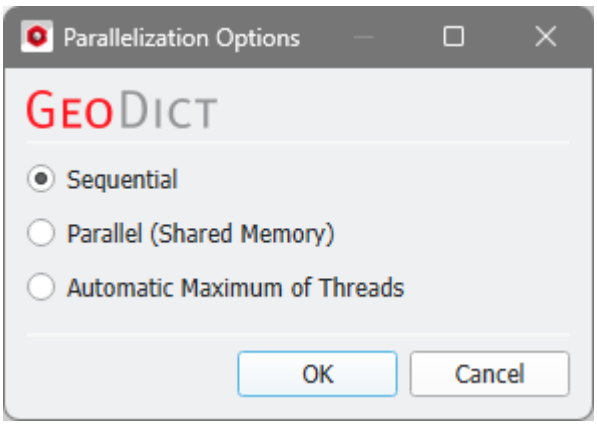
Parallelization

Control how many threads are used for the computation. Parallelization is possible if your license and hardware allow it.

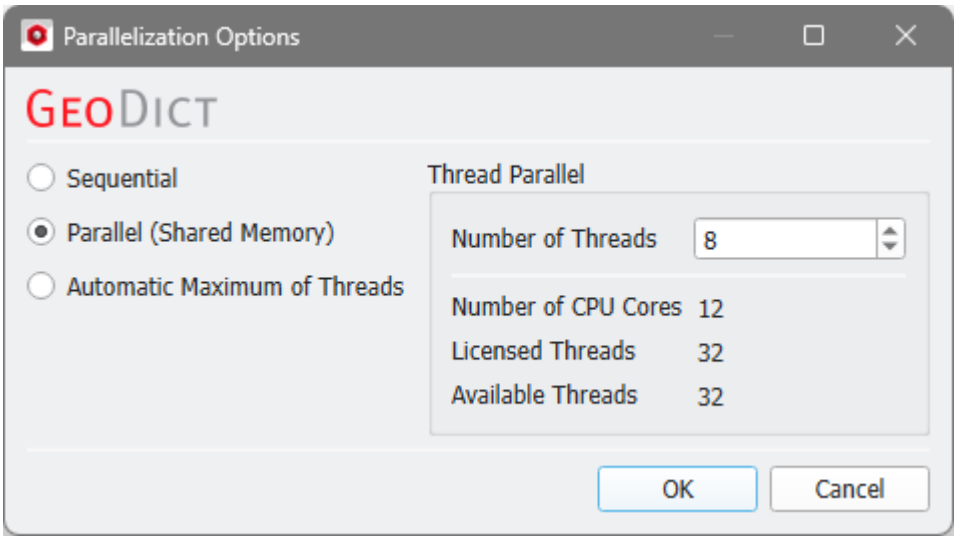
The **Parallelization Options** dialog opens when clicking the **Edit** button and you can choose between **Sequential**, **Parallel (Shared Memory)**, or **Automatic Maximum of Threads**.



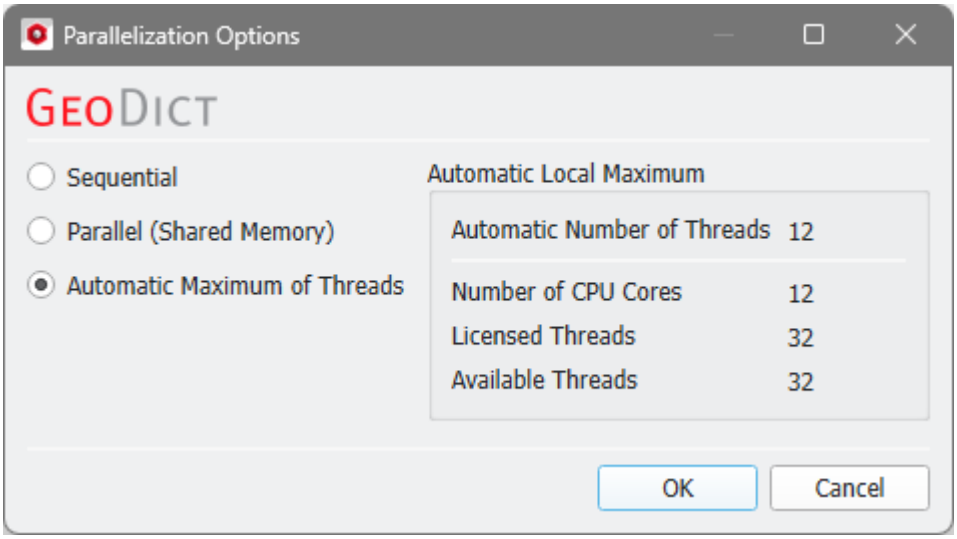
Selecting **Sequential** will not apply parallelization and only one thread is used for the computation.



When **Parallel (Shared Memory)** is selected, the **Number of Threads** can be entered. Below, the **Number of CPU Cores** that the current machine has, the maximum number of **Licensed Threads** and the number of those licensed threads that are available (**Available Threads**) are shown in the dialog. Of course, the maximal number of parallel processes you can use, is the smallest of those three numbers.



If **Automatic Maximum of Threads** is selected, the number of parallel processes is automatically selected for optimal speed, based on the CPU cores and licensed parallel processes.



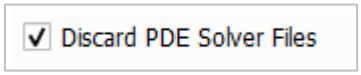
The **Automatic Local Maximum** of processes is automatically selected, which is the minimum of **Number of CPU Cores**, **Licensed Threads**, and **Available Threads**.

Additionally, for the EJ solver, calculations can run on a Linux cluster.

For more details on how to set up and run parallel computations, consult the High Performance Computing chapter.

Discard PDE Solver File

Checking **Discard PDE Solver Files** causes the deletion of all intermediate computation files, such as log files and flow field files.



Only the content of the final GeoDict result file (*.gdr) is stored.

While having the benefit of saving hard disk storage place, discarding intermediate solver files has also the effect of disabling the 3D visualization of the results.

Write Diffusion Flux into Solution File

Additional 3D data can be added to the solution *.hht files for visualization or later analysis. With **Write Diffusion Flux into Solution File** the Diffusion Flux in the three coordinate directions is saved, allowing a detailed analysis of the field. The size of the result files and the memory requirements increase when selecting this option.

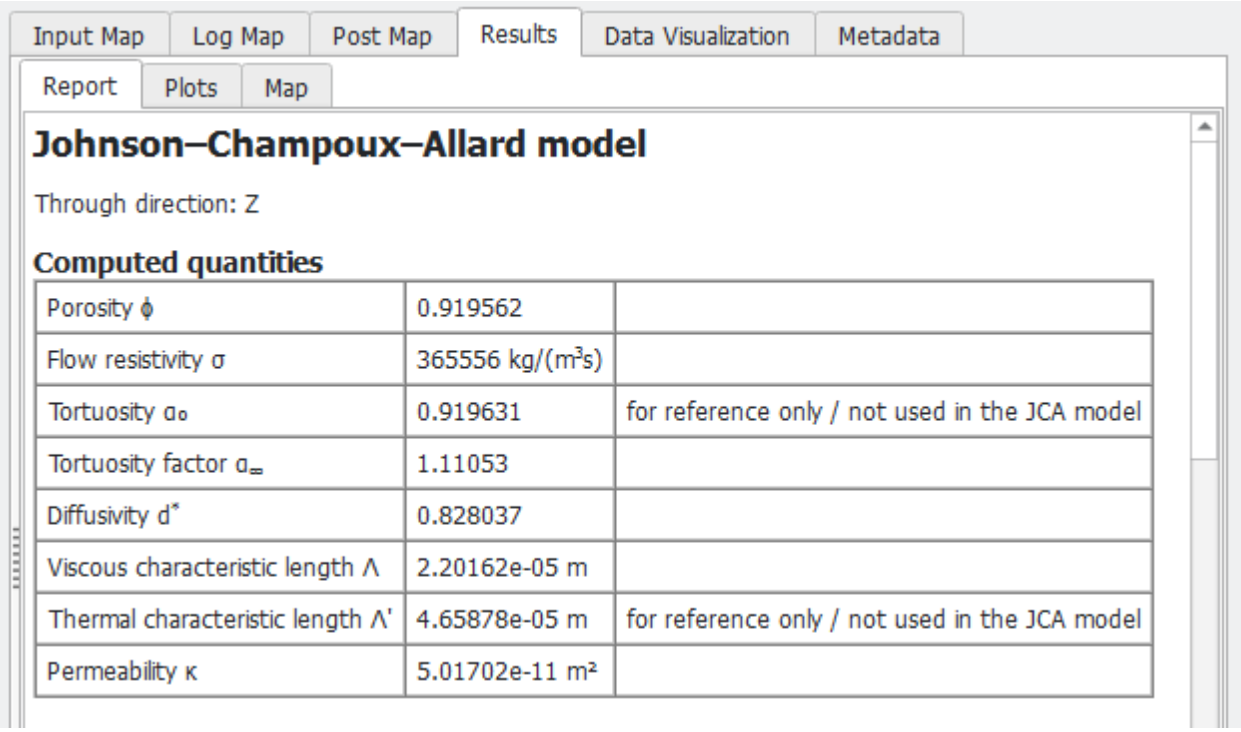
Equations and References

This tab displays formulas and references which are explained in more detail in the Theoretical Background 7.

1.3.2 Results

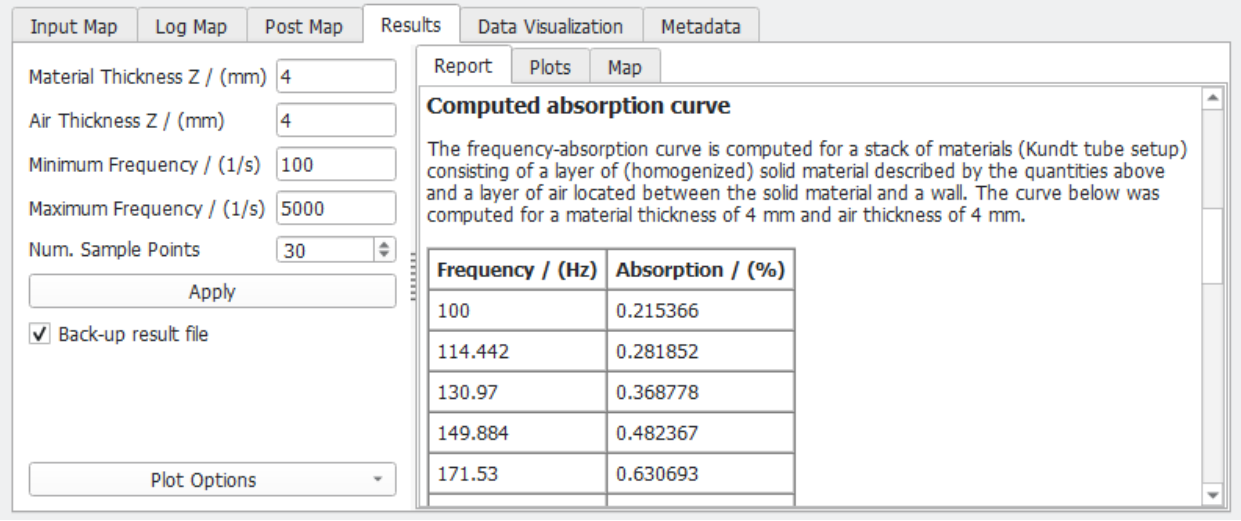
Click **OK** to input the entered parameters and then click **Run** in the AcoustoDict section to start the command.

The results are immediately shown in the opening Result Viewer after the process is finished, the screenshot below shows the calculated acoustic parameter values for the Johnson–Champoux–Allard model. The **Results→Report** subtab shows porosity, flow resistivity, tortuosity, tortuosity factor, diffusivity, viscous characteristic length, thermal characteristic length, and permeability in the direction of interest.



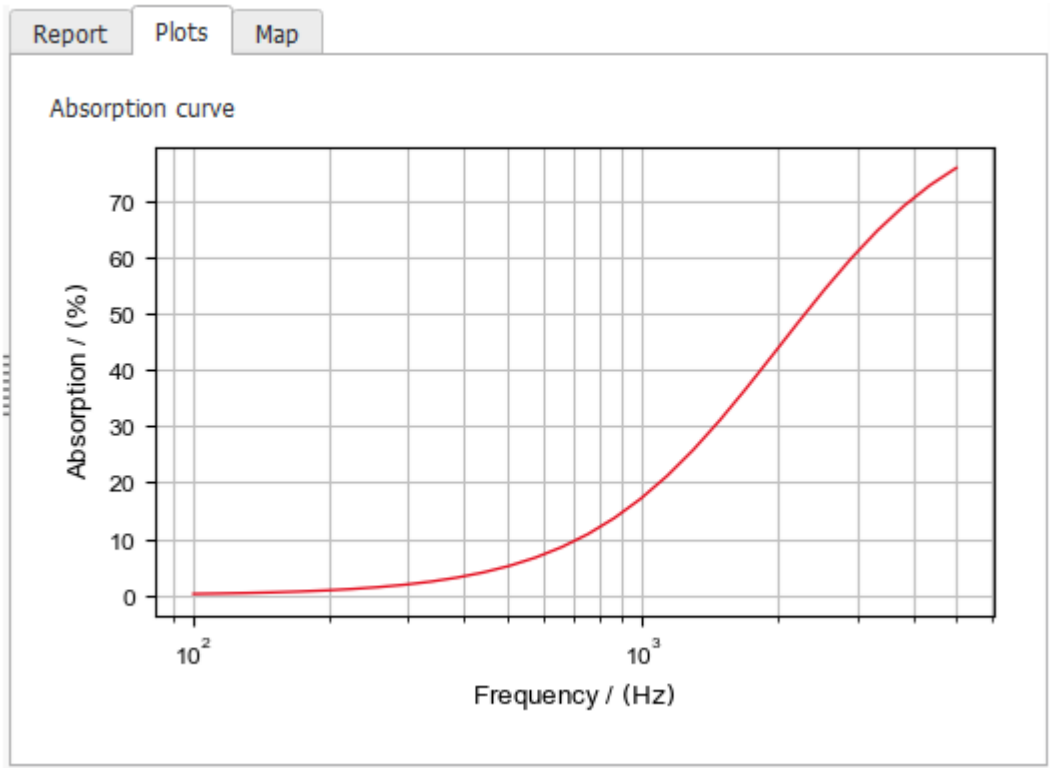
Absorption curve

The frequency–absorption curve is computed for a stack of materials in Kundt tube setup, consisting of a layer of (homogenized) solid material described by the computed flow resistivity and porosity and a layer of air located between the solid material and a wall.



The thickness of the material and the air layer can be set in the panel on the left, as **Material Thickness Z** and **Air Thickness Z**. By default, 4 mm are used for both values.

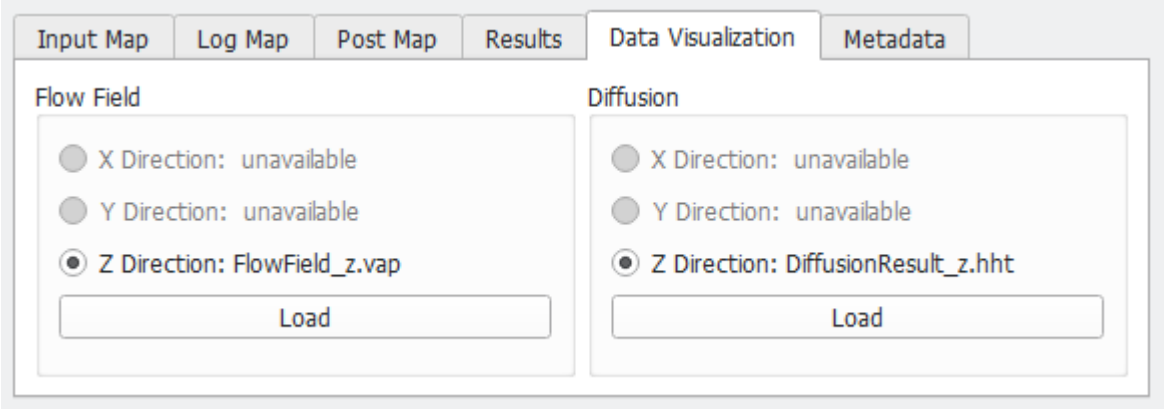
The absorption is computed in a range given by the **Minimum Frequency** and **Maximum Frequency** values, using the given number of **Sample Points**. The curve is shown in the **Results→Plots** subtab.



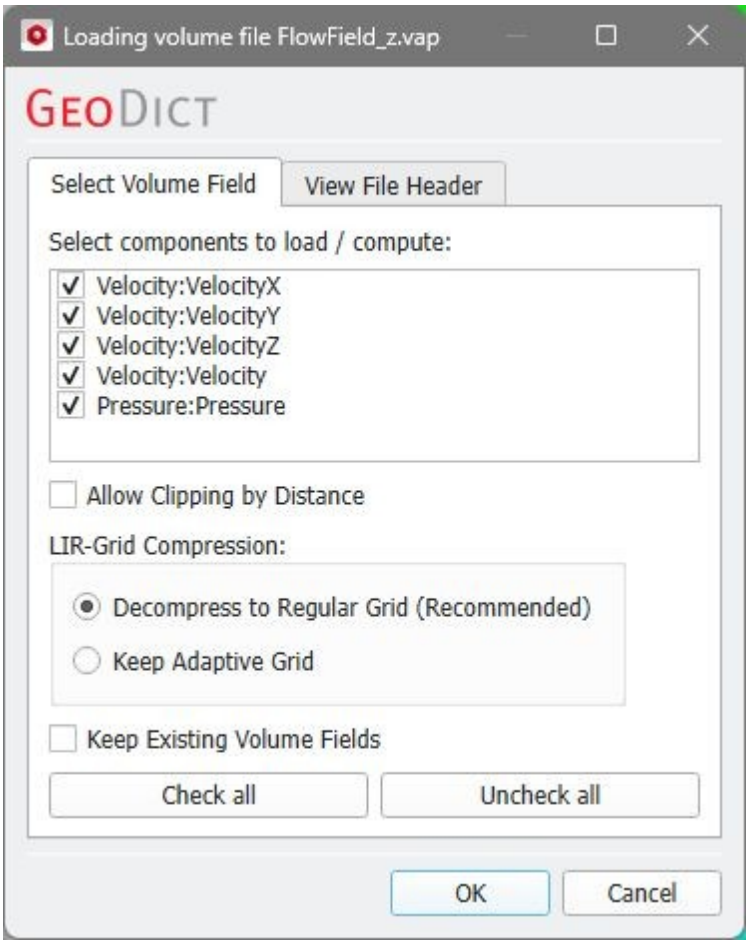
The **Results→Map** subtab gives access to the media-dependent acoustic parameters values computed for the selected acoustic model.

1.3.3 Data Visualization

Under the **Data Visualization** tab, the results can be loaded for graphical visualization in 2D-Cross section view or 3D-Rendering. Flow fields and concentration fields that have been calculated can be visualized by clicking **Load**.



In the opening **Loading volume file** dialog, select the volume fields you want to load. Supplemental fields, as, e.g., the Velocity:Velocity field shown in the dialog, will be computed from the saved fields in the file.



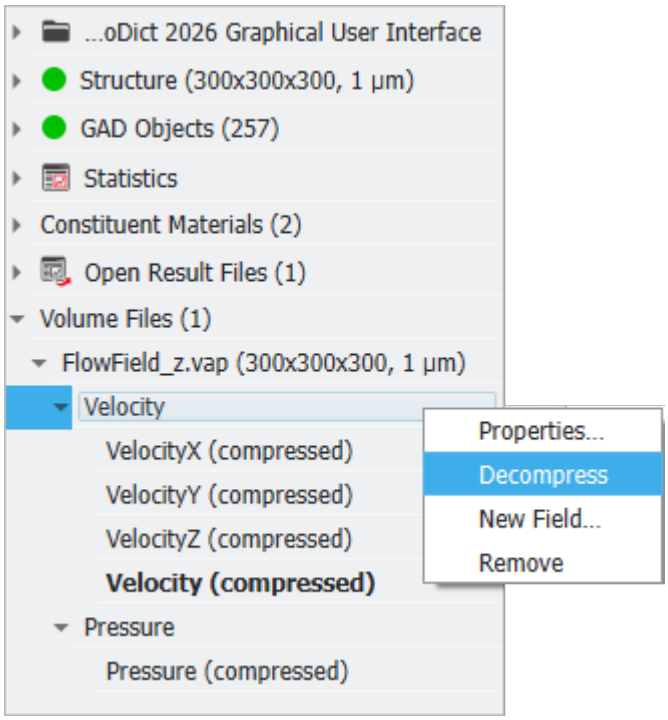
Selecting **Allow Clipping by Distance** also computes a distance field using a signed Euclidean distance transform (see the MatDict-EDT chapter for more information). The distances can then be used to threshold the other loaded volume fields.

A compressed field is saved when checking **Write Compressed Volume Fields** under the Solver tab of the **LIR Solver Options** dialog. If a compressed volume field is opened, it is possible to choose either **Decompress to Regular Grid** (which is the recommended option) or **Keep Adaptive Grid**, which means to load the field in compressed form.

Important! Some visualization features of volume fields (e.g the visualization of streamlines) are available only if the field is loaded in decompressed form.

However, loading a compressed volume field needs less memory, which can be advantageous for large structures.

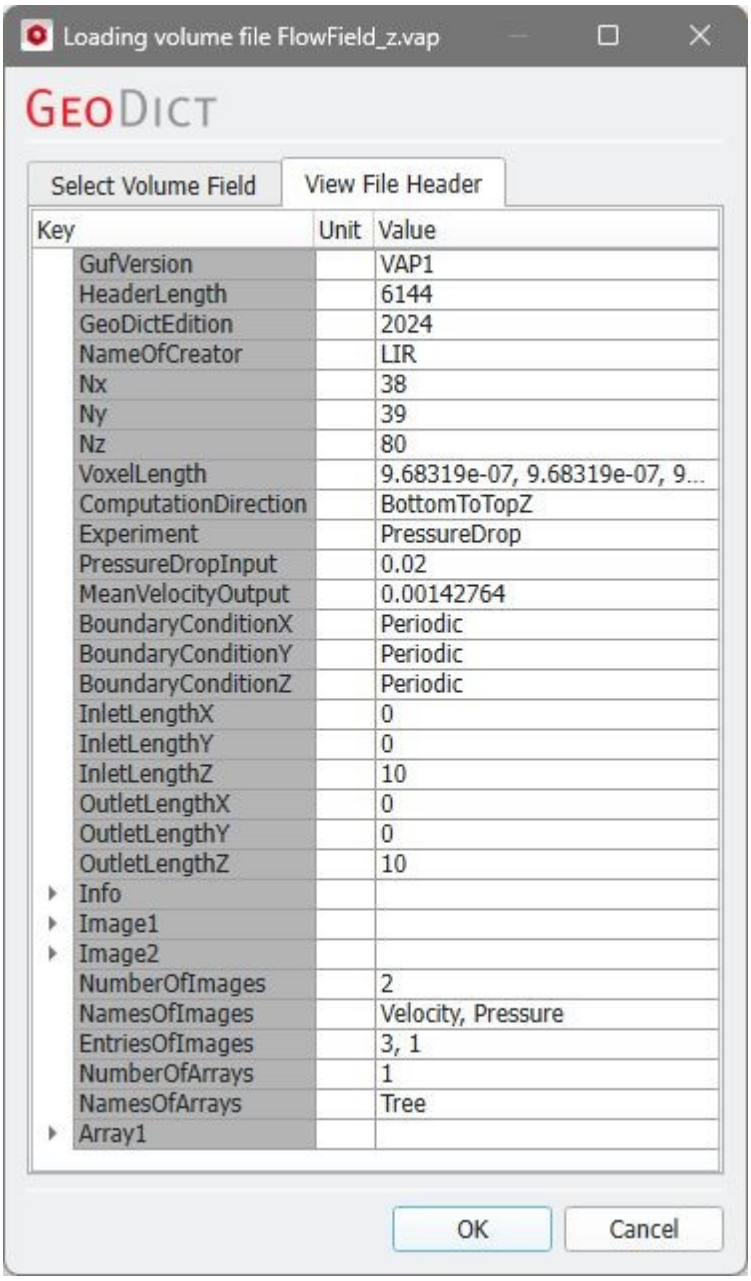
It is also possible to load a volume file in compressed form and decompress it later. In the project status section on the left, right click on the volume image and choose **Decompress**.



Check **Keep existing Volume Fields**, if already loaded volume fields should be kept in the GeoDict memory.

With the buttons **Check all** and **Uncheck all**, the fields from the volume file you want to load can be selected or deselected at once.

In the **View File Header** tab you can see the header of the volume file. The header provides information about the domain size, voxel length, boundary conditions, and many more. Nothing can be edited in this tab, only the available information, depending on the volume file type, is shown.



Know how! You can open a volume file with a text editor to read the header which is the only human-readable part. However, it is more convenient to view this during import in GeoDict. Moreover, large volume files take a long time to open in a text editor, or the editor may be unable to open them at all.

Find more about the content of the header in volume files in the GeoPy Scripting chapter.

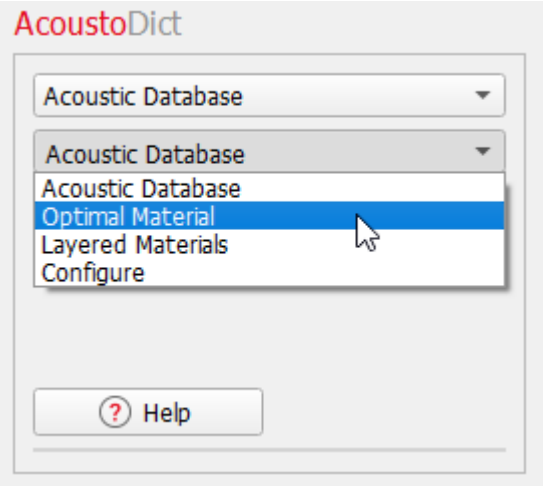
Clicking **OK** starts the import of the volume file.

The options for the visualization of results are explained in detail in the Visualization chapter.

1.4 Acoustic Database

The flow resistivity values calculated with the Delany–Bazley model can be entered into your AcoustoDict **Database** to predict the frequency-dependent acoustic absorption of their structure. A default database is included in the installation and - if the default installation settings have been kept - it is located at: `c:\Users\username\GeoDict2026\AcoustoDictDataBase`. This editable AcoustoDict database can be used to store own results and later predict the acoustic properties of virtual materials at different degrees of compression.

To access the AcoustoDict database, select **Acoustic Database** from the pull-down menu in the AcoustoDict section. Four options are available: **Acoustic Database**, **Optimal Material**, **Layered Materials**, and **Configure**.



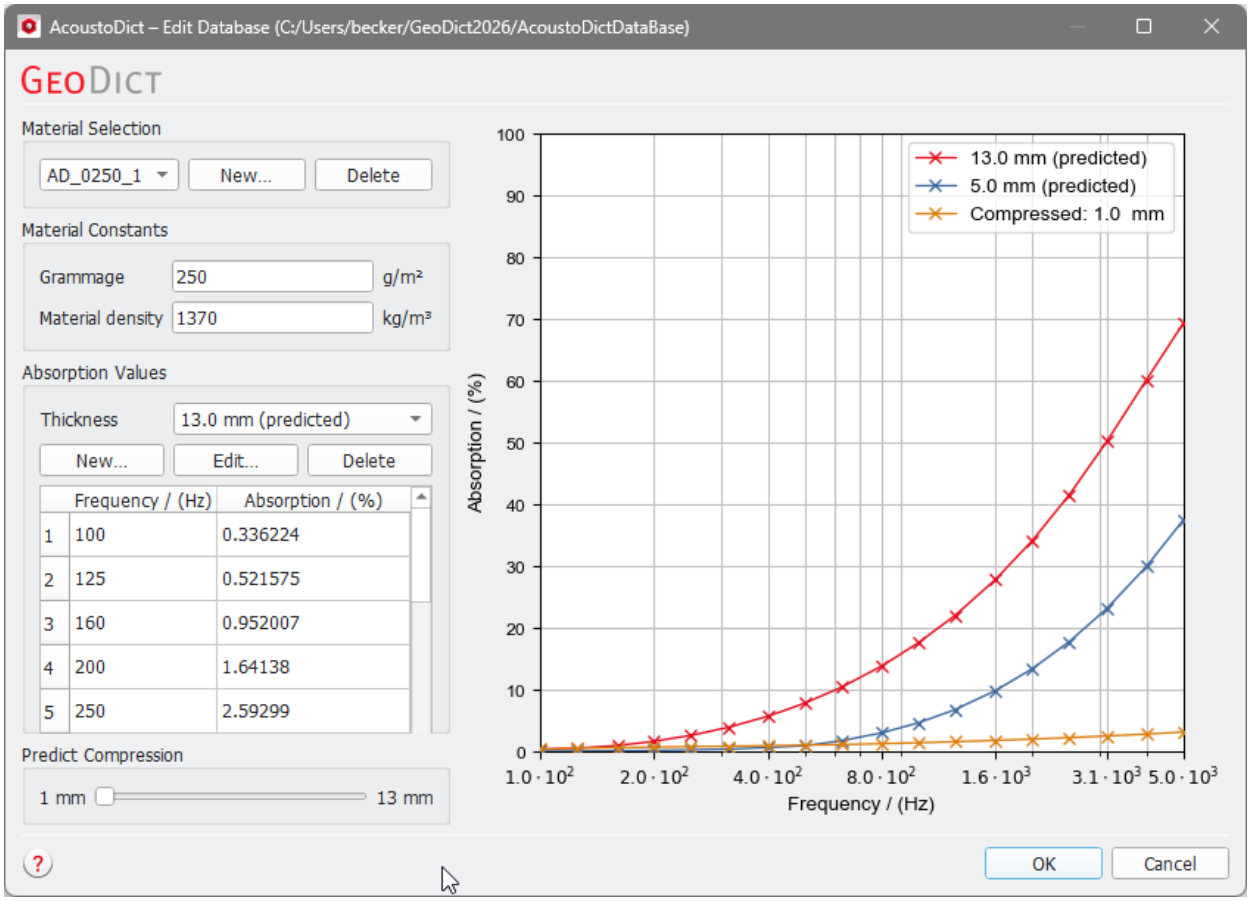
The **Acoustic Database** works differently from a usual GeoDict command, and the **Record** and **Run** buttons disappear from the AcoustoDict section when **Acoustic Database** is selected. When opening a dialog, the whole functionality of modifying and accessing the database takes place inside the dialog widgets. No macro can be stored for those actions and no results files are created during those actions.

Acoustic Database options

- Acoustic Database 40
  Edit the acoustic database.
- Optimal Material 43
  Find a combination of material and thickness that best matches a desired absorption curve.
- Layered Materials 45
  Simulate the acoustic absorption of a stack of material layers.
- Configure 47
  Change the path to the AcoustoDict database and set the default frequencies.

1.4.1 Acoustic Database

To edit the **Acoustic Database**, select **Acoustic Database** from the pull-down menu and click the Options's **Edit...**. button in the **AcoustoDict** section. The **AcoustoDict Edit Database** dialog box opens, showing the path to the database in the caption.



Material Selection

Select the currently displayed material from the pull-down menu in the **Material Selection** panel.

To add a new materials to the database, click **New....** and enter the **Material Name**. For new materials, no absorption values are initially given and have to be entered in the **Material Constants** and **Absorption Values** panels below.

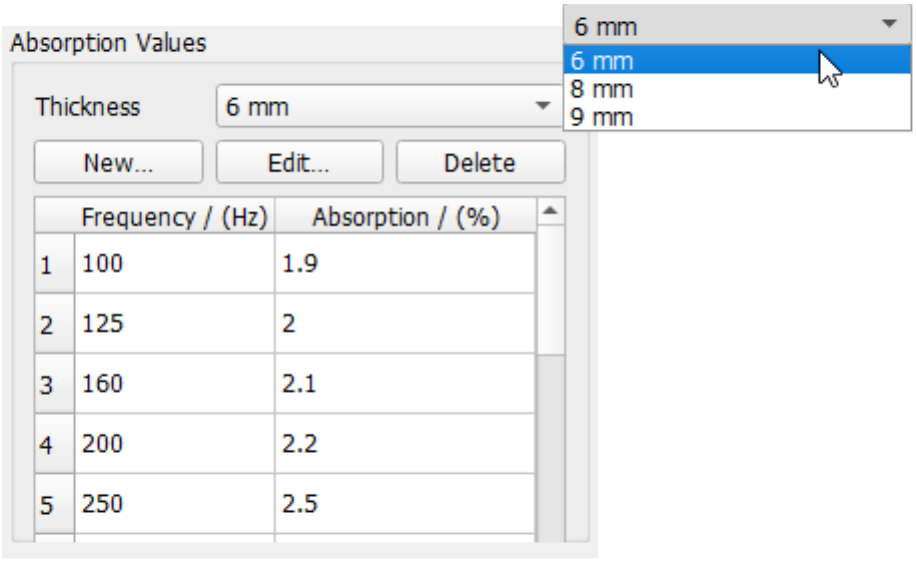
Materials can be removed from the database by clicking **Delete** and confirming the deletion.

Material Constants

Grammage and **Material density** of the selected material are shown (and are editable) in the **Material Constants** panel. The **Material density** is the density of the constituent material of the fibers, not the density of the porous medium.

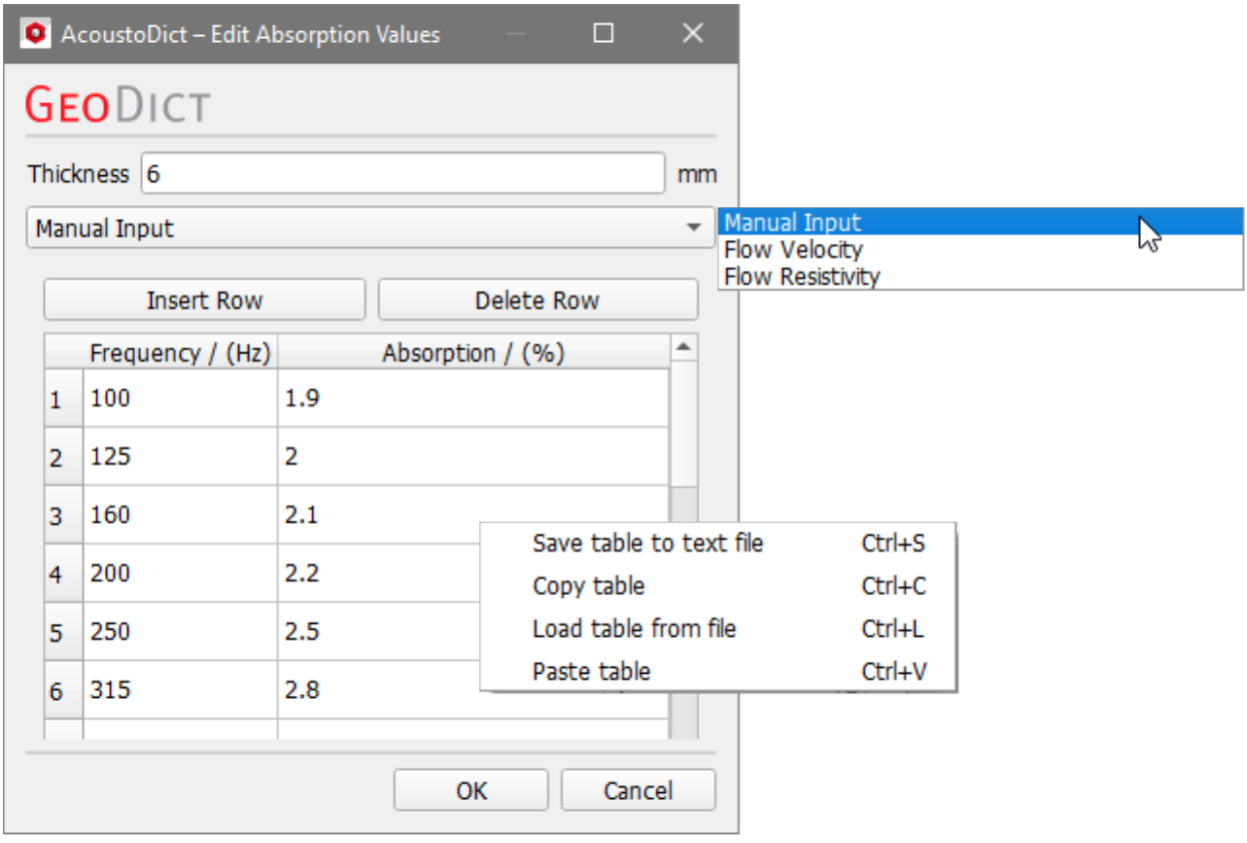
Absorption Values

In the **Absorption Values** panel, a table shows the sound absorption at given frequencies for the selected material. Absorption values may exist for various compression levels of the same material, where the level of compression is described by its **Thickness**.



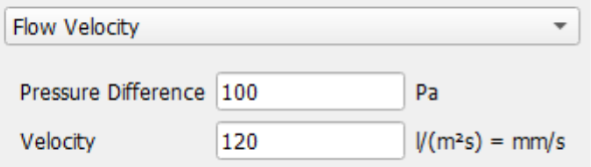
Click **Delete** to remove all data for the selected thickness.

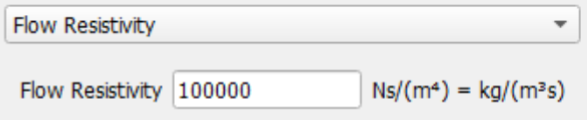
The table displayed in the **Absorption Values** panel is not editable. To change the table values, click **Edit...** to open the **Edit Absorption Values** dialog.



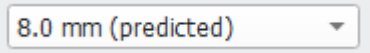
In the first line, you can change the material's **Thickness**. Below, select how the data will be entered. Select **Manual Input** to enter the acoustic absorption of real materials, experimentally measured in an impedance tube, and available in a data sheet. You may use the **Insert Row** and **Delete Row** buttons to enter the values manually in the table, or you might right-click into the table and save the table date to a text file, edit the text file and load the data back into the table, or simple use Ctrl+C & Ctrl+V to copy & paste from the clipboard.

Alternatively, the sound absorption values may be predicted from a measured or simulated flow resistivity. The fluid flow results can be given either by the **Flow Resistivity** or by **Pressure Difference** and **Velocity**.





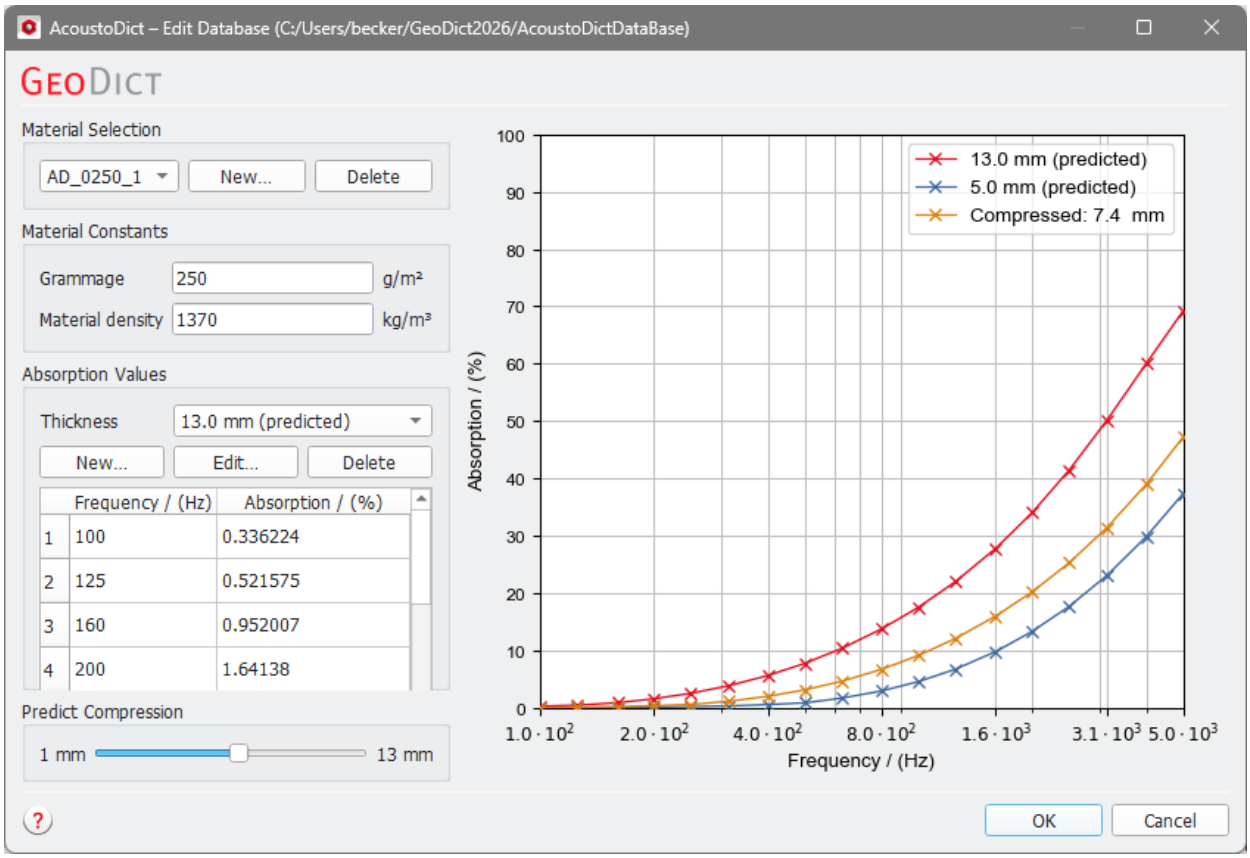
The Delany–Bazley[6] model is then used to compute the frequency-dependent absorption values. After clicking **OK**, the computed absorption values are entered into the table and the word **(predicted)** is added behind the thickness value in the drop-down-menu:



Click **New...** to enter frequency and absorption values for an additional compression level. Use the **Edit Absorption Values** dialog as described above. The entered values can be edited at any time by clicking the **Edit...** button. This reopens the **Edit Absorption Values** dialog box. Finally, click **OK** in the **Edit Database** dialog box to save the newly entered or the edited materials in the AcoustoDict Database.

Predict Compression

When data for the same material at different degrees of compression exists, the chart on the right hand side of the dialog shows the absorption curves for each material thickness. In this case, the slider in the **Predict Compression** panel at the bottom left corner is activated and you can obtain predicted acoustic absorption curves for arbitrary thicknesses.



The prediction relies on the fact that the Delany–Bazley model allows to compute the sound absorption from the viscous flow resistivity of the porous material. This is combined with an approximation for the dependency of the viscous flow resistivity σ of the porous material on the thickness d of the material. AcoustoDict uses the ansatz function

$$\sigma(d) = \alpha\rho(d)^{\beta}, \tag{23}$$

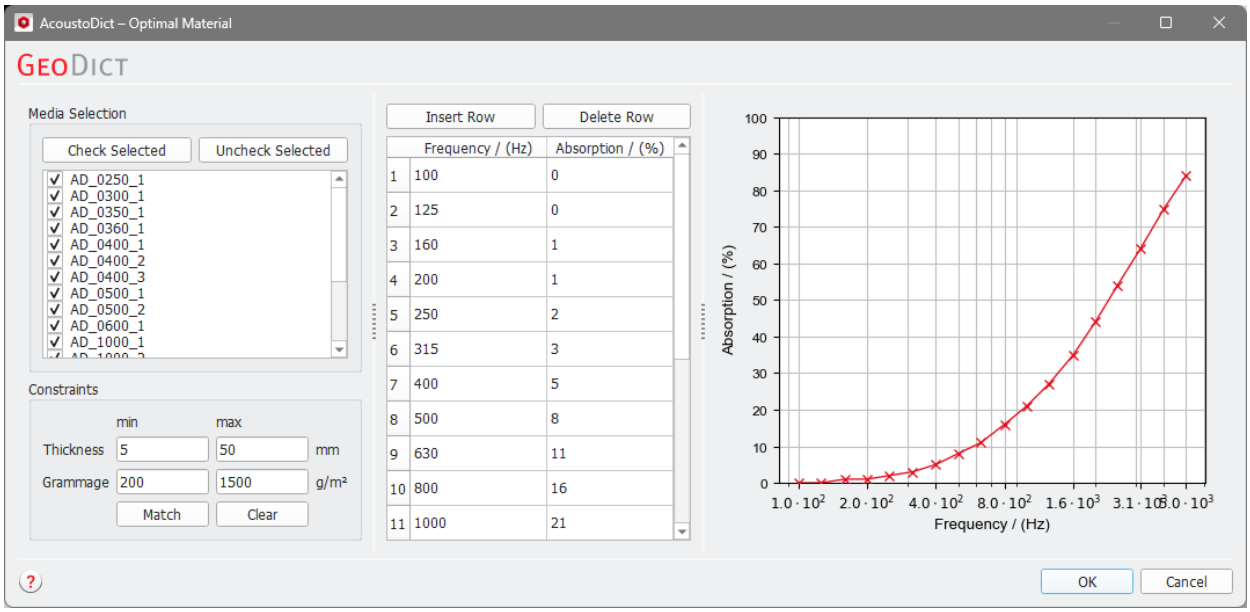
where $\rho(d)$ is the thickness-dependent density of the porous material. Under the assumption of mass conservation, the density $\rho(d)$ can be computed from the **Material density** of the constituent fiber materials, the porosity of the uncompressed layer and the rate of compression. Note that the **Grammage** and the **Material density** of the constituent fiber material need to be entered in the **Material Constants** panel for this computation to be accurate.

When values for at least two different thicknesses (i.e., at least two pairs σ_i, d_i) are known, the ansatz function can be solved for α and β. After α and β are determined, the viscous flow resistivity σ can be estimated for any material thickness, and thus a prediction of the sound absorption with the Delany–Bazley model becomes possible.

1.4.2 Optimal Material

Once the AcoustoDict database has been populated, selecting **Optimal Material** and clicking **Match...** allows finding a combination of material and thickness that best matches a desired

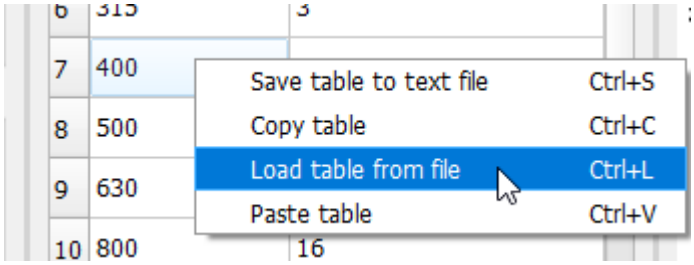
absorption curve. In the opening dialog box, in the **Media Selection** panel, select the database materials to be considered for the optimization. As default, all materials are selected.



To deselect one material, click on the name to highlight it and then click **Uncheck Selected** or just uncheck the box. To deselect multiple materials, it is faster to press SHIFT+Left mouse button while moving the mouse over a range of materials and then, click **Uncheck Selected**. The selection of unselected materials is done in the same way but clicking **Check Selected** instead.

In the **Constraints** panel, enter minimum and maximum **Thickness** as well as the **Grammage**. All materials that fall outside the specified grammage interval or that are uncompressible to the indicated thickness range are highlighted in red in the database and are ignored in the matching.

Enter the values for the desired absorption curve in the table, which consists of **Frequency** and corresponding **Absorption** coefficient pairs. Select one of the rows and use **Insert Row** or **Delete Row** to add or eliminate pairs of values. Alternatively, right-click into the table, save the table date to a text file, edit the text file and load the data back into the table. Or simply copy & paste data from the clipboard using the common Ctrl+C & Ctrl+V shortcuts.



The curve of these frequency/absorption values is displayed on the right and updated while editing the values.

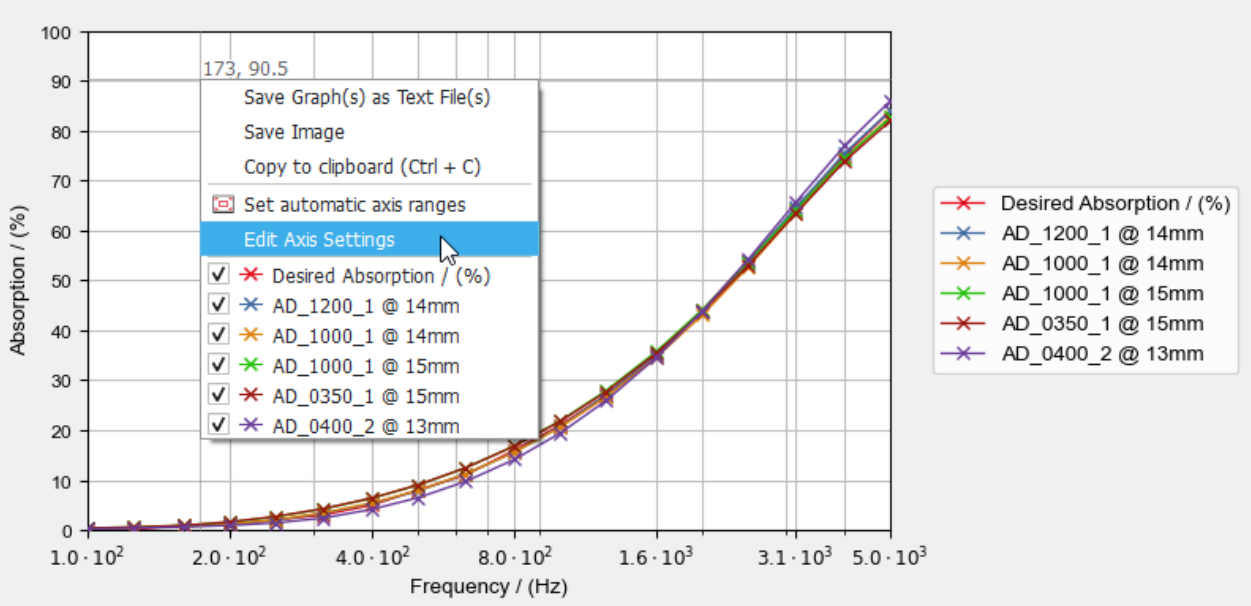
When clicking **Match** in the **Constraints** panel, AcoustoDict considers the materials fulfilling the given thickness and grammage constraints and computes the absorption curve at different thicknesses within the given interval.

A graph with the five materials that best match the desired absorption characteristics is displayed on the right with the name of the materials in the legend. The table now includes new columns with the absorption values at the given frequencies for these five materials:

	Frequency / (Hz)	Desired Absorption / (%)	AD_1200_1 @ 14mm	AD_1000_1 @ 14mm
1	100	0	0.287984	0.294815
2	125	0	0.448435	0.458933
3	160	1	0.73029	0.746989
4	200	1	1.13125	1.11815
5	250	2	1.94666	2.0524

Notice that the thickness of the database materials is also taken into account and, therefore, the name of the materials indicates at which thickness of that material the best match occurs. Drag the corners and expand the dialog box to better observe the graph and the table columns. Right-click into the table to save the data in a text file.

Right-click inside the graph to change the graph settings:



Clicking **Clear** in the **Constraints** panel makes the values of the matched materials in the table and their curves in the graph disappear. Afterwards, you can start over trying to match other materials in the database.

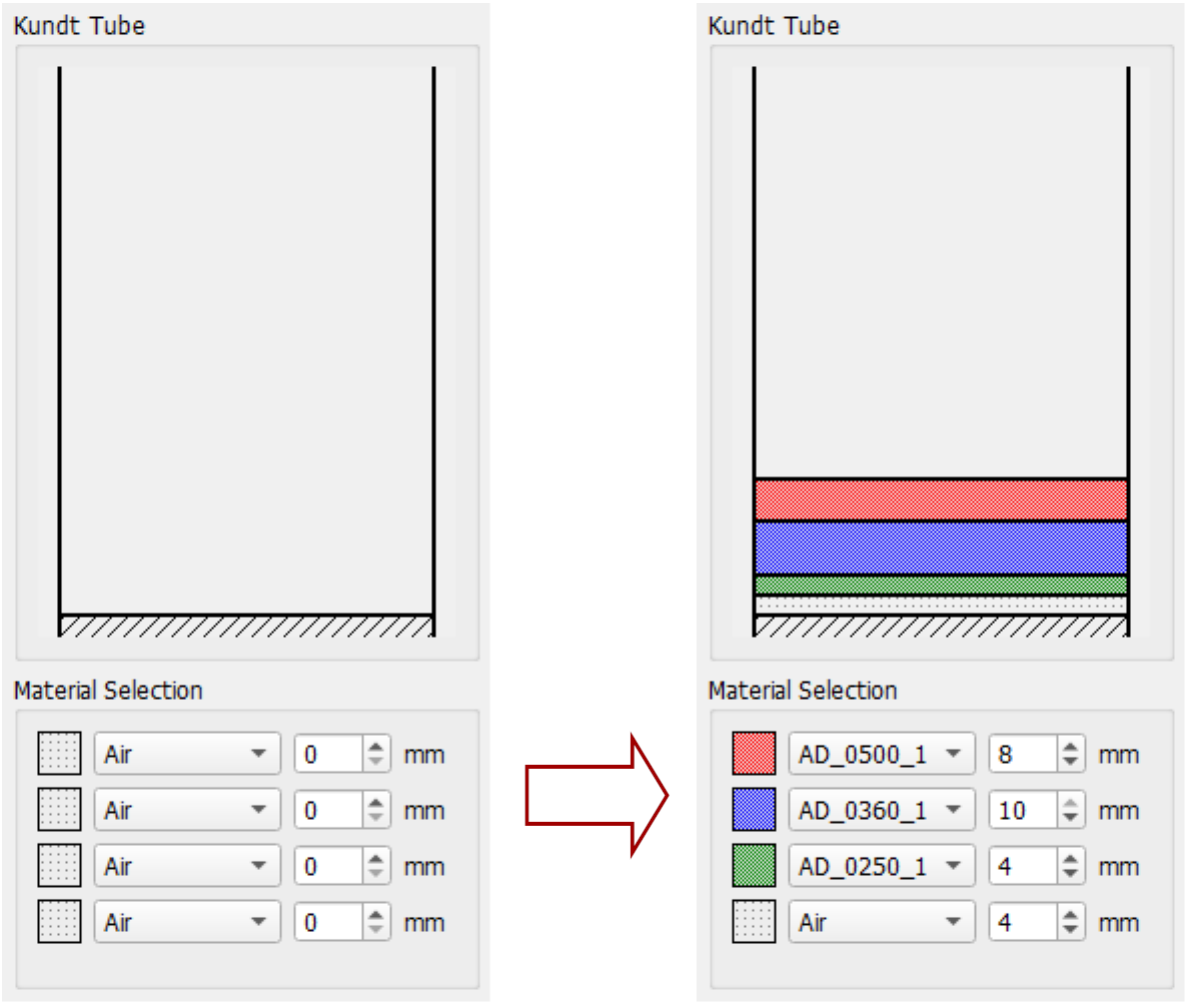
1.4.3 Layered Materials

Layered Materials is designed to simulate the acoustic absorption of a stack of material layers chosen by the user.

Click **Stack...** to open the dialog box. On the left, the **Kundt Tube** panel shows a cross-section schematic drawing of a virtual impedance tube for the measurement of the absorption

coefficient of materials. The heavy backing plate is shown at the bottom as a block of slanted stripes.

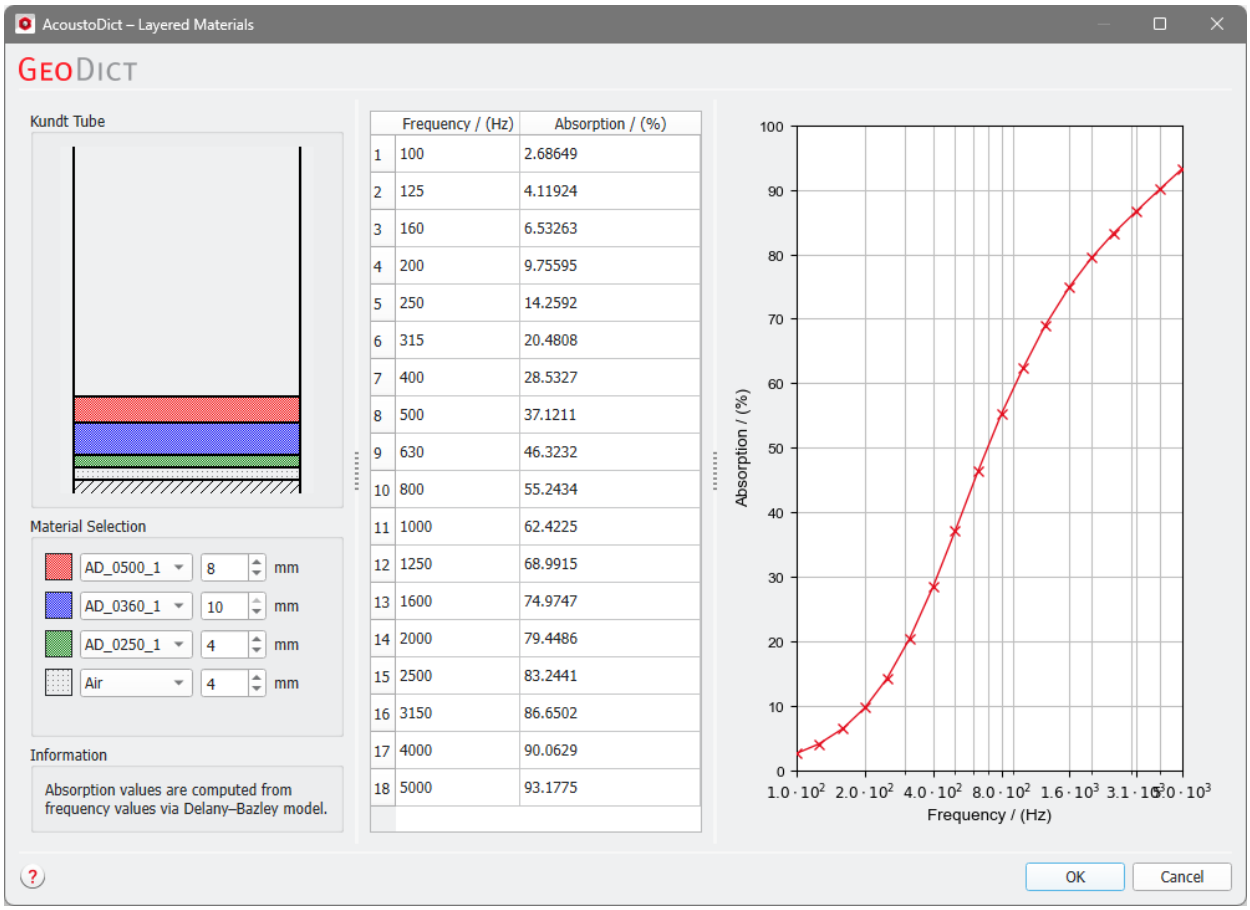
Under the **Material Selection** panel, select materials from the AcoustoDict database using the pull-down menus. Stacks of up to four different materials can be constructed. All materials in the database are available, as well as **Air** to allow for air gaps in the stacked multilayer construction.



A color is assigned to every material (or air) layer and the thickness of the layer can be directly entered or selected through the up-down arrows. If the multilayer construction should have less than four layers, unused layers can be set to **Air** and **0 mm**.

While the layers are being stacked, the predicted acoustic absorption values of the multilayer stack at various frequencies are already listed in the table and the frequency/absorption curve for the complete multilayer construction is displayed on the right.

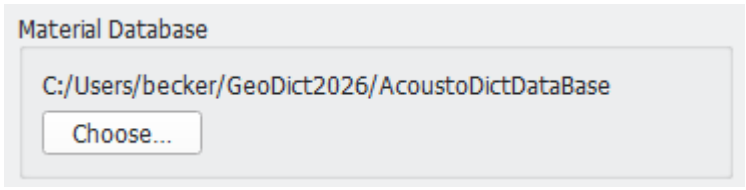
Countless variations of the multilayer construction can be built in real time.



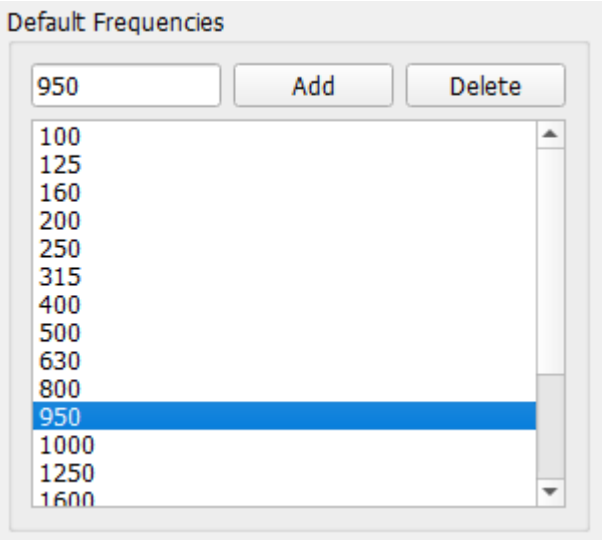
The computation of the acoustic surface impedance Z_s follows equations (4) 5 - (6) 5

1.4.4 Configure

Select **Configure** and click **Configure...** to open the **AcoustoDict Configure** dialog box, where you can change the path to the AcoustoDict database as desired. Each material in the AcoustoDict database is stored in a single file within this folder and can be individually copied, exchanged, or shared with other users of GeoDict.



In the **Default Frequencies** panel, predefine the set of frequencies that are used when entering new absorption values into the Acoustic Database 41.



By predefining the frequencies to match those routinely registered by the user's instrument during measurement, only the **Desired Absorption [%]** values have to be manually entered in the table when real measurements are transferred to AcoustoDict.

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