Design of Pleated Filters by Computer Simulations

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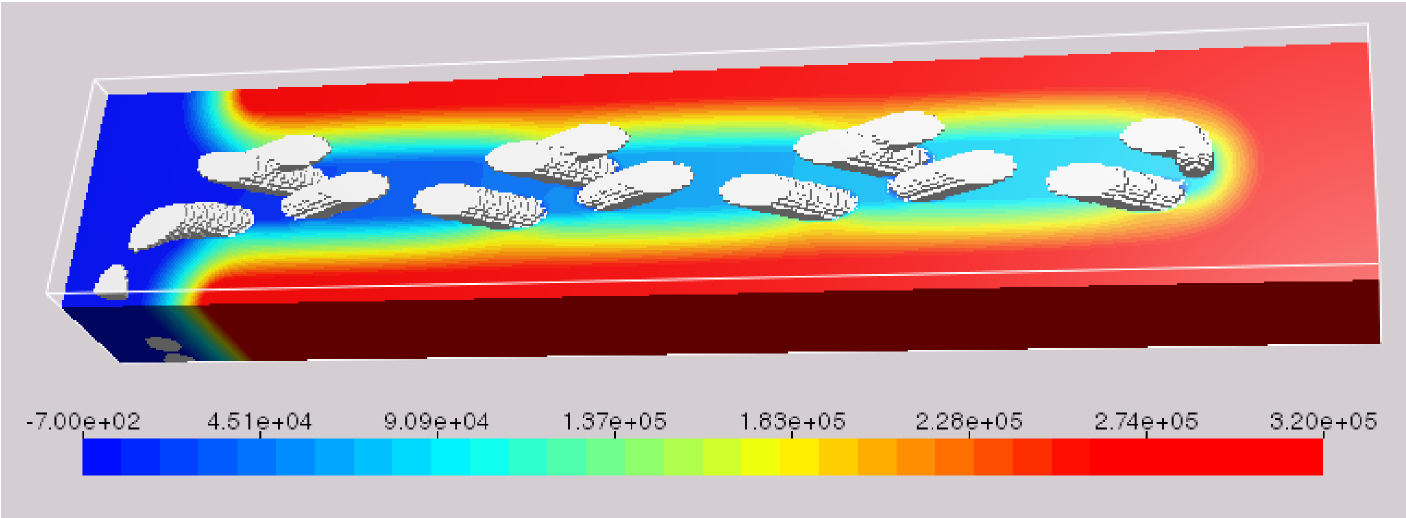
= Fraunhofer Institute for Industrial Mathematics

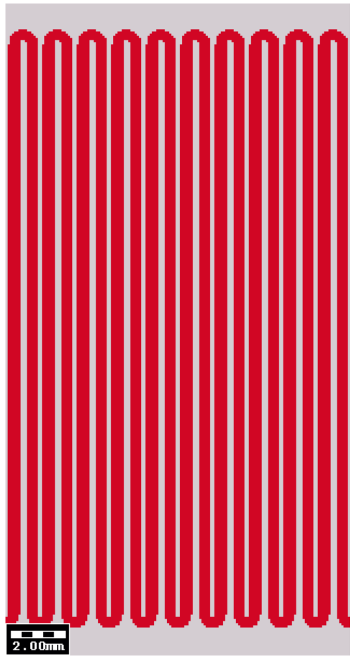


Overview

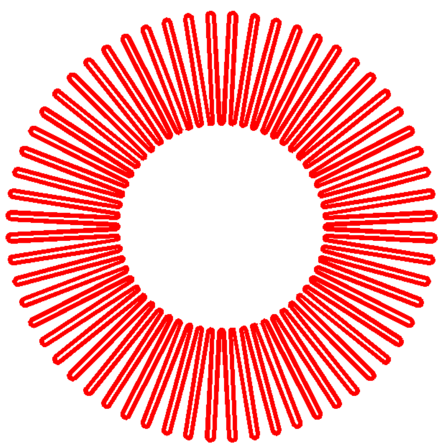
- 3d Pleat model and its input parameters
- Flow model: computation of the pressure drop
- Results for air filtration – 2d parameter studies
- Results for oil filtration – influence of 3d support structure

Model for pleats and flow

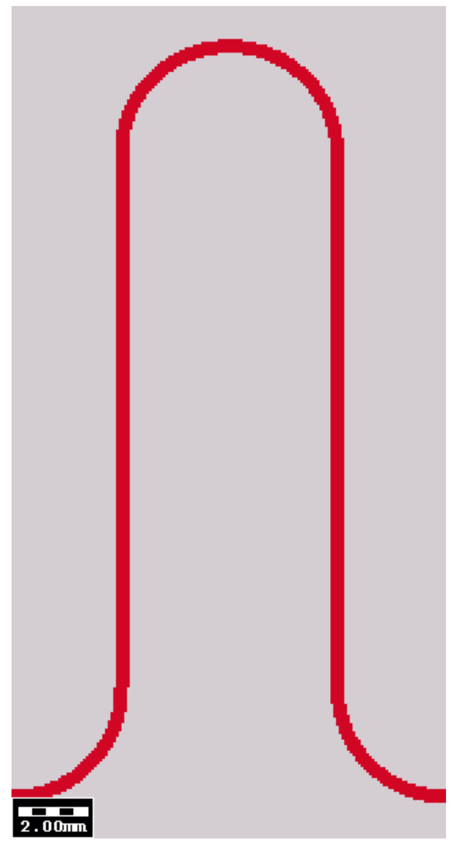
Pleated air filter

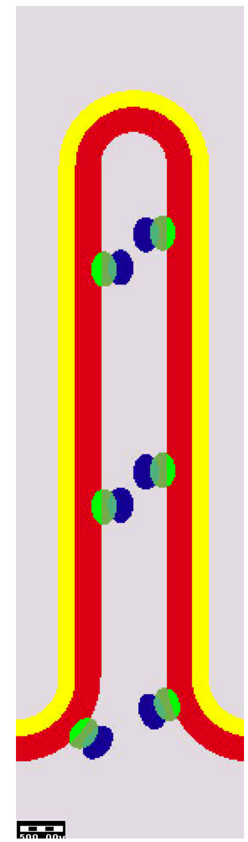


Pleated oil filter



Direction of the flow

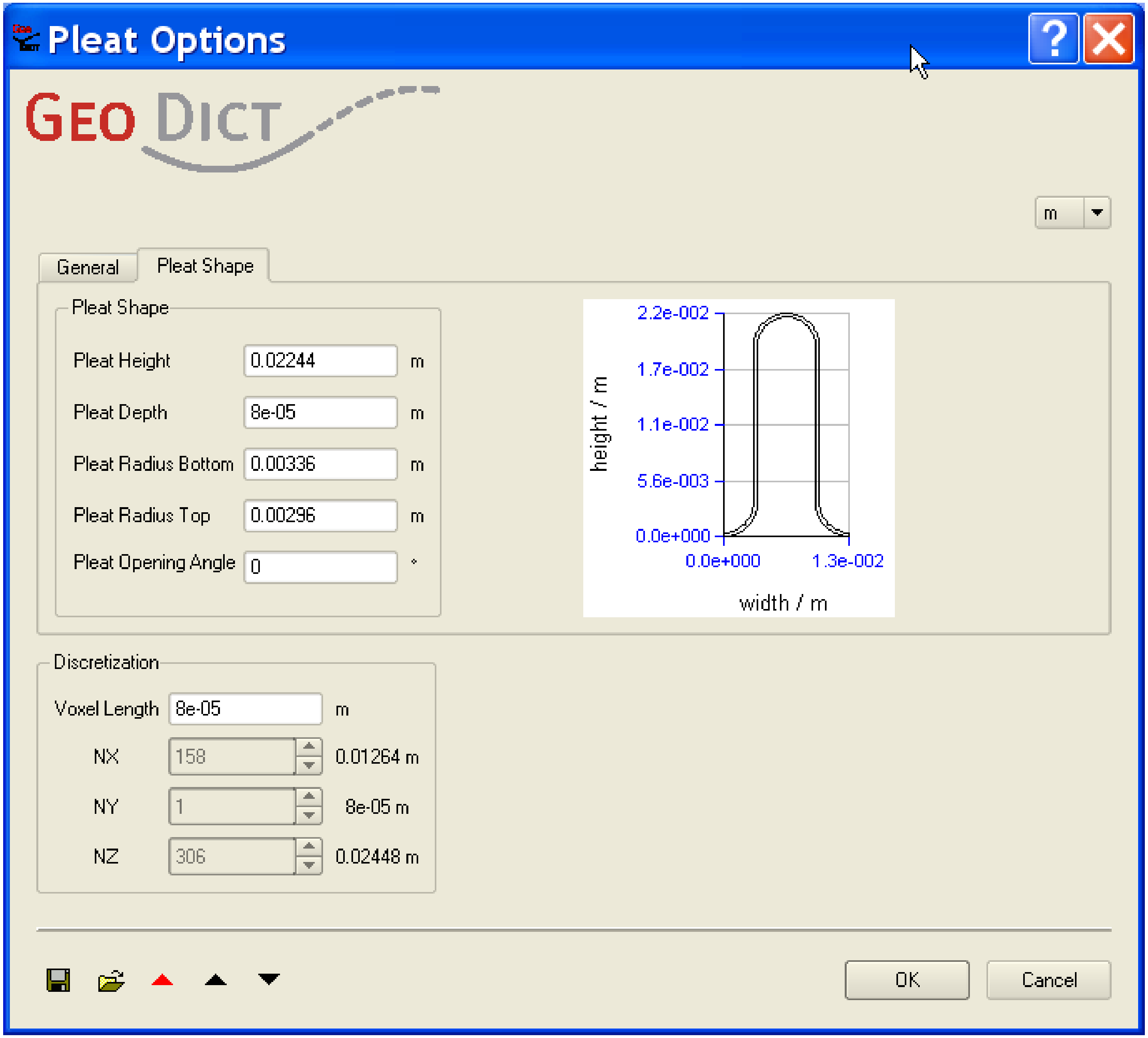




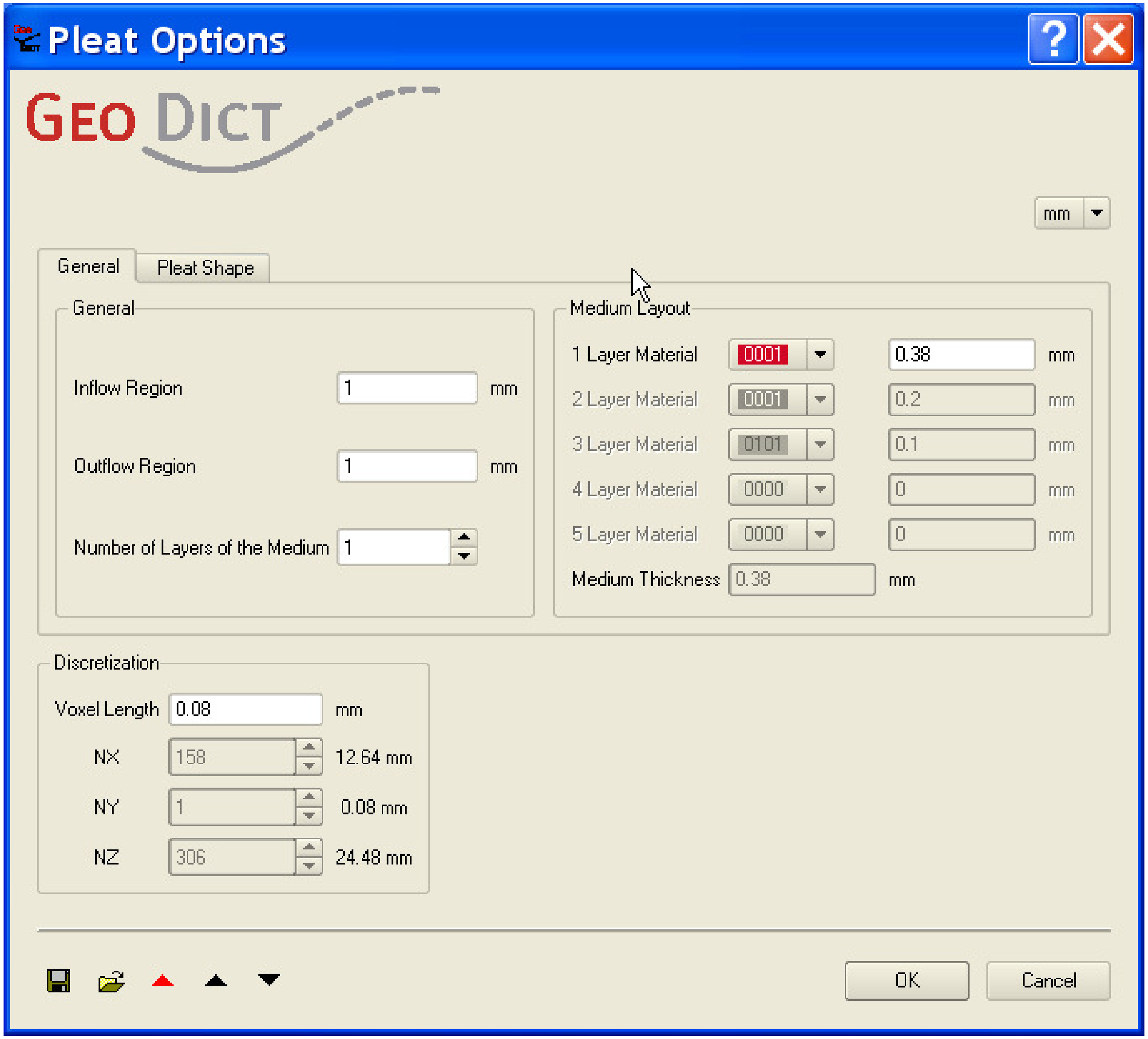
Red = filter media

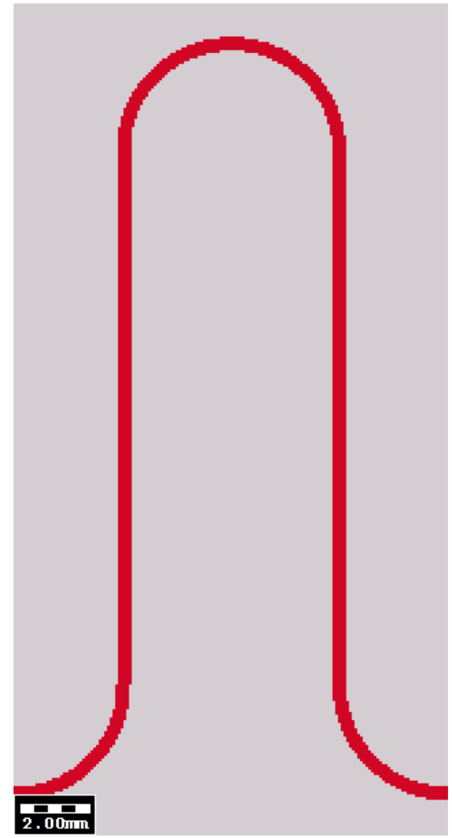
Yellow = second layer

Shape Pleat Options

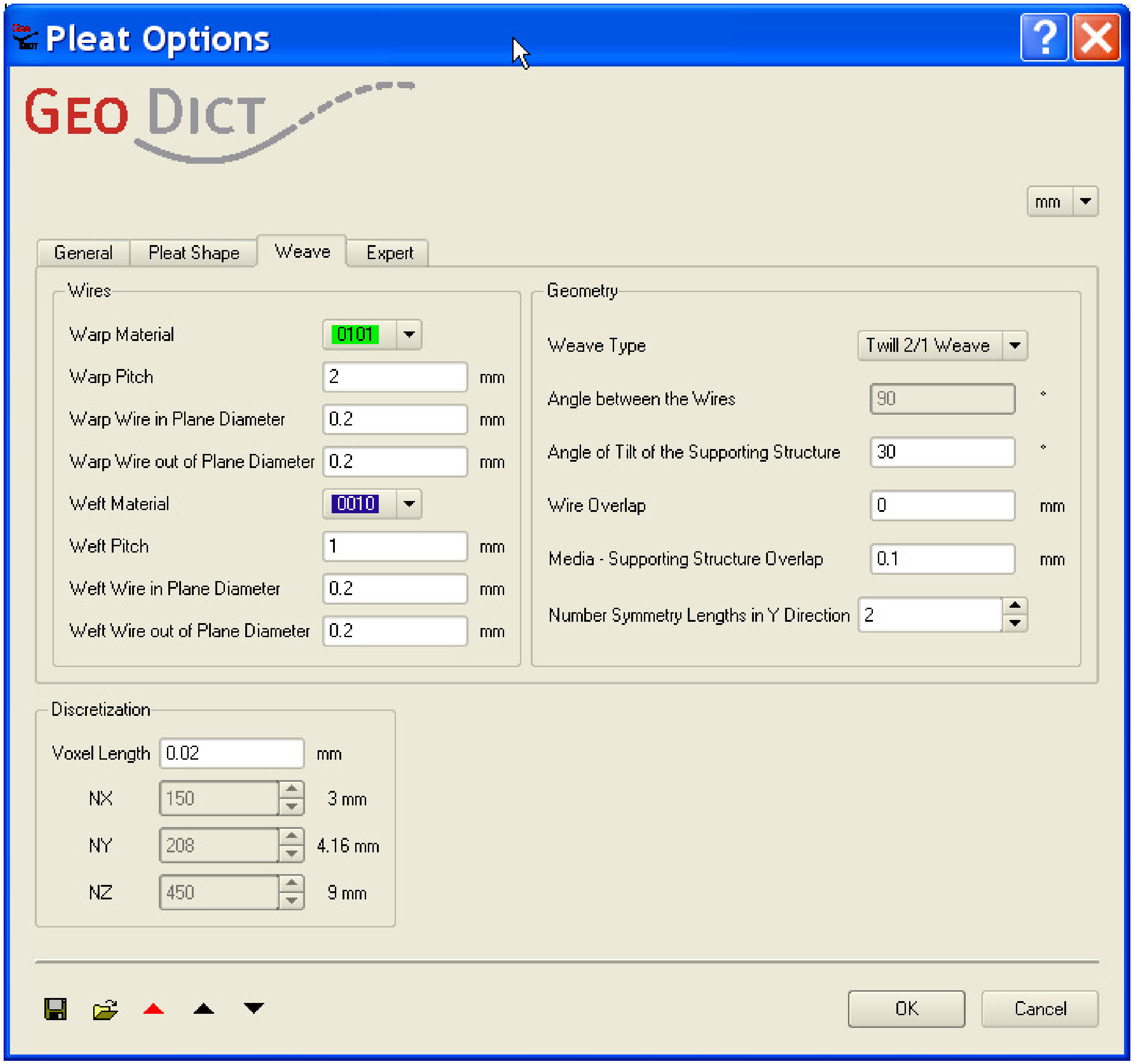


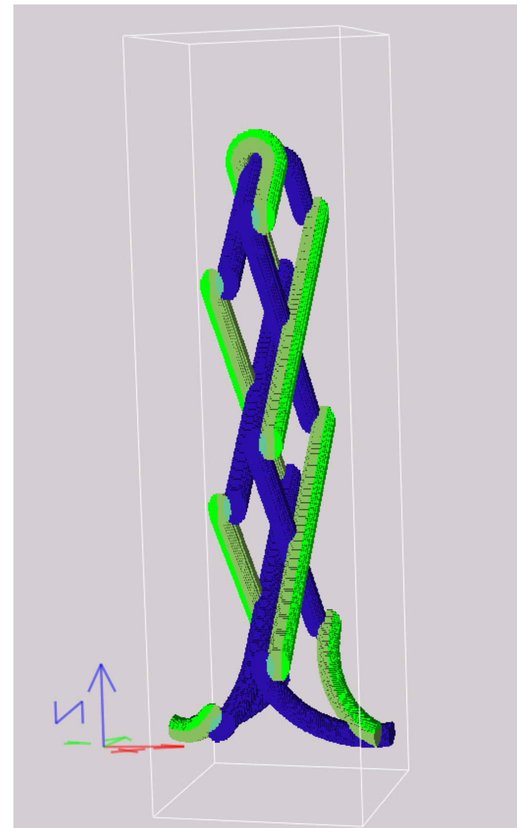
General Pleat Options



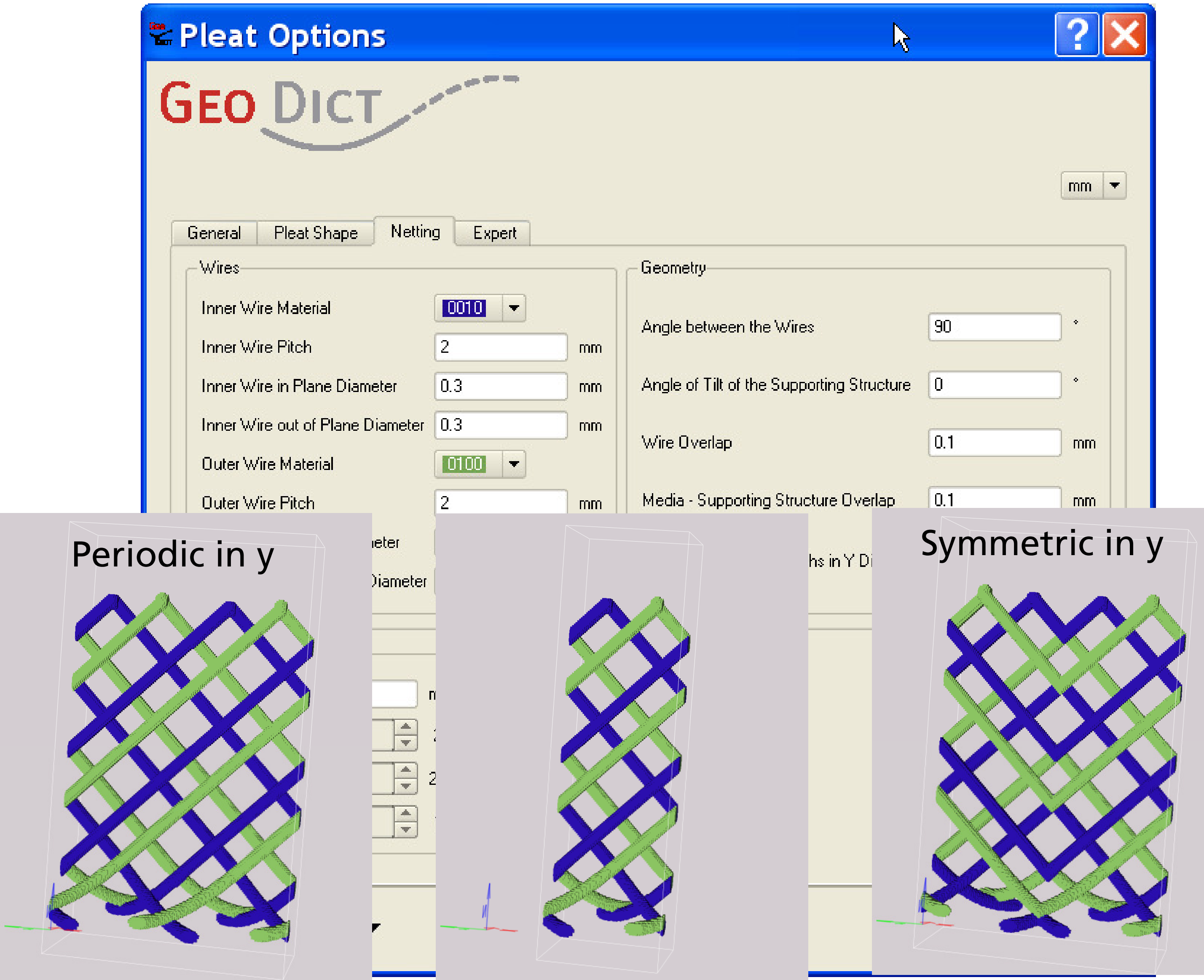


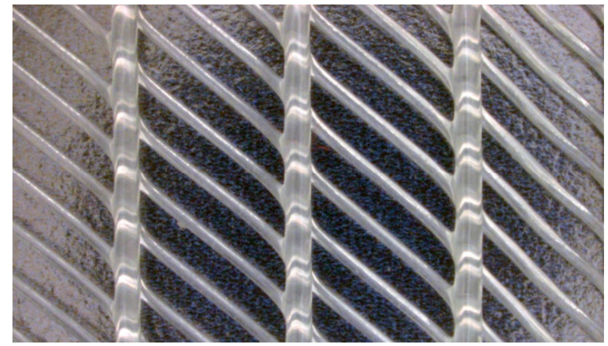
Weave Pleat Options

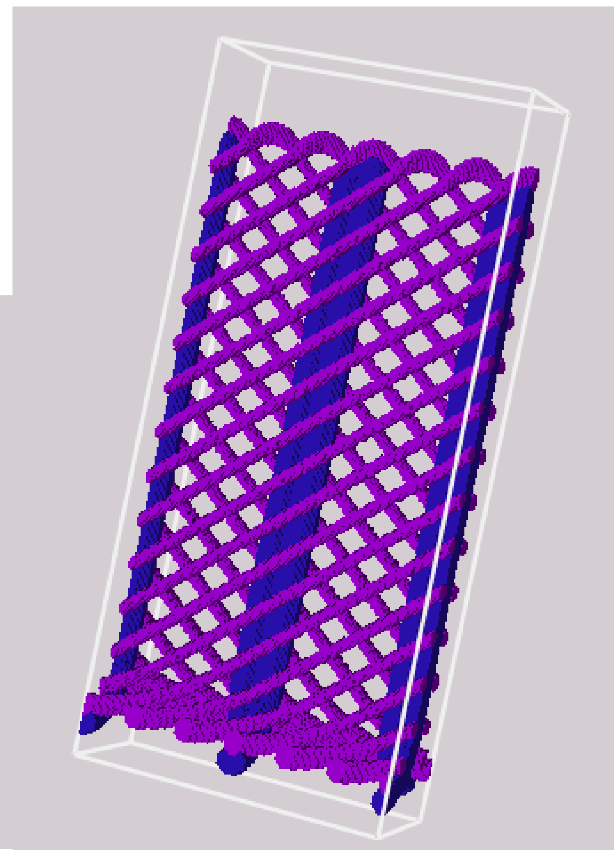




Netting Pleat Options







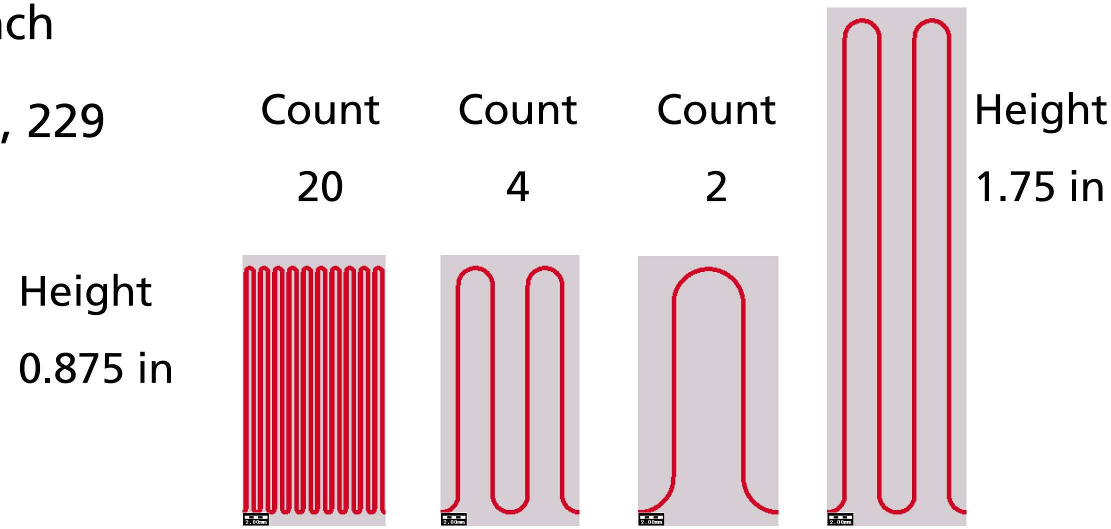
Pressure Drop Optimization by Chen et al.[1]

Pleat **heights**: 0.875, 1.75, 3.5 and 5.25 inch

Pleat **counts**: 2, 3, 4,…, 20 pleats / inch

Pleat **media**: 252, 213, 233, 220, 224, 229

[1]Chen, Pui and Liu, *Aerosol Science and Technology*, 1995



Grade no.	DOP Efficiency	Permeability [m²]	Thickness	Base weight
252	99.99 % ULPA	7.25e-13	0.38	73
213	99.985 % HEPA	1.03e-12	0.38	73
233	98.5 %	2.26e-12	0.38	73
220	95 %	3.20e-12	0.38	73
224	90-95% ASHRAE	7.67e-12	0.38	73
229	80-90 % ASHRAE	1.10e-11	0.38	73

Pressure Drop Optimization translated to GeoDict

Heights: 0.875, 1.75, 3.5 and 5.25 inch = 0.2224, 0.04448, 0.08888 and 0.13336 meter

Counts: 2, 3, 4,…, 20 pleats / inch ~ 2*(0.00336+0.00296), … meter pleat **width**

Media: 252, 213, 233, 220, 224, 229 ~ 7.25e-13, … meter² **permeability**

```
GeoDict:VaryMacro{
  FileName pui.gvm
  NumberOfVariables 7
  Variable1:ValueList 7.25e-13,1.03e-12,2.26e-12,3.20e-12,7.68e-12,1.10e-11
  Variable1:CoupledWith NONE
  Variable2:ValueList 0.02224,0.04448,0.08888,0.13336
  Variable2:CoupledWith NONE
  Variable3:ValueList 0.00336,0.00232,0.00176,0.00144,0.00128,0.00112,0.00096,0.00088,0.00080,0.00072,0.00064,0.00056,0.00056,0.00048
  Variable3:CoupledWith NONE
  Variable4:ValueList 0.00296,0.00192,0.00136,0.00112,0.00088,0.00072,0.00064,0.00048,0.00048,0.00032,0.00024,0.00024,0.00016,0.00016
  Variable4:CoupledWith 3
  Variable5:ValueList 252,213,233,220,224,229
  Variable5:CoupledWith 1
  Variable6:ValueList 0.875in,1.750in,3.500in,5.250in
  Variable6:CoupledWith 2
  Variable7:ValueList  2, 3, 4, 5, 6, 7, 8, 9,10,12,14,16,18,20
  Variable7:CoupledWith 3
}
```

Commands: structure generation and pressure drop computation

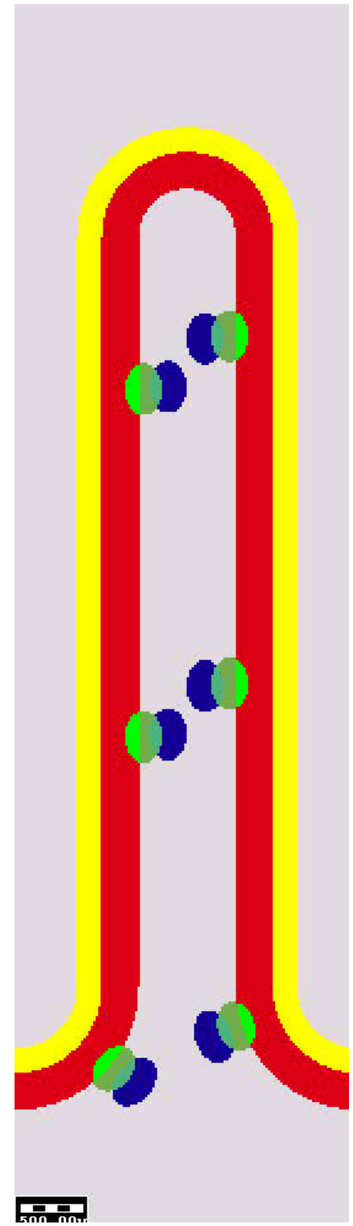
```
PleatGeo:WithoutSupportingMesh {
FileName
InflowRegion 0.001
MediaThickness1 0.0004
MediaThickness2 0
MediaThickness3 0
MediaThickness4 0
MediaThickness5 0
NumberLayers 1
OutflowRegion 0.001
PleatDepth 8e-05
PleatHeight %2
PleatMaterial1 1
PleatMaterial2 0
PleatMaterial3 0
PleatMaterial4 0
PleatMaterial5 0
PleatOpeningAngle 0
PleatRadius1 %3
PleatRadius2 %4
VoxelLength 8e-05
}
```

```
PleatDict:SolveEFVStokesBrinkmann {
NumberOfNodes 1
Parameters:FluidDensity 1.204
Parameters:FluidViscosity 1.834e-05
Parameters:MeanVelocity 0.508
Parameters:PressureDifference 0.02
Parameters:PressureEnabled 0
Permeabilities:Color1 %1,%1,%1
Permeabilities:Color10 0,0,0
Permeabilities:Color11 0,0,0
Permeabilities:Color12 0,0,0
Permeabilities:Color13 0,0,0
Permeabilities:Color14 0,0,0
Permeabilities:Color15 0,0,0
Permeabilities:Color2 0,0,0
Permeabilities:Color3 0,0,0
Permeabilities:Color4 0,0,0
Permeabilities:Color5 0,0,0
Permeabilities:Color6 0,0,0
Permeabilities:Color7 0,0,0
Permeabilities:Color8 0,0,0
Permeabilities:Color9 0,0,0
RelaxationPressure 0.8
RelaxationVelocity 0.5
SolverData:Accuracy 1e-05
SolverData:AddedFreeSpace 0
SolverData:DirectionEnabledX 0
SolverData:DirectionEnabledY 0
SolverData:DirectionEnabledZ 1
SolverData:DiscardTemporaryFiles 0
SolverData:FileName Pleat_%5_%6_%7.gdr
SolverData:MaxNumberOfIterations 100000
SolverData:MirrorVolume 0
SolverData:NumberOfProcesses 8
SolverData:PermeabilityCheckInterval 20
SolverData:Restart 0
SolverData:RestartFileName
SolverData:ScalingType 1
SolverData:ScalingValue 1
SolverData:SlipLength 0
SolverData:SolverType 0
SolverData:StoppingCriterion 1
}
```

Stokes-Brinkmann formulation

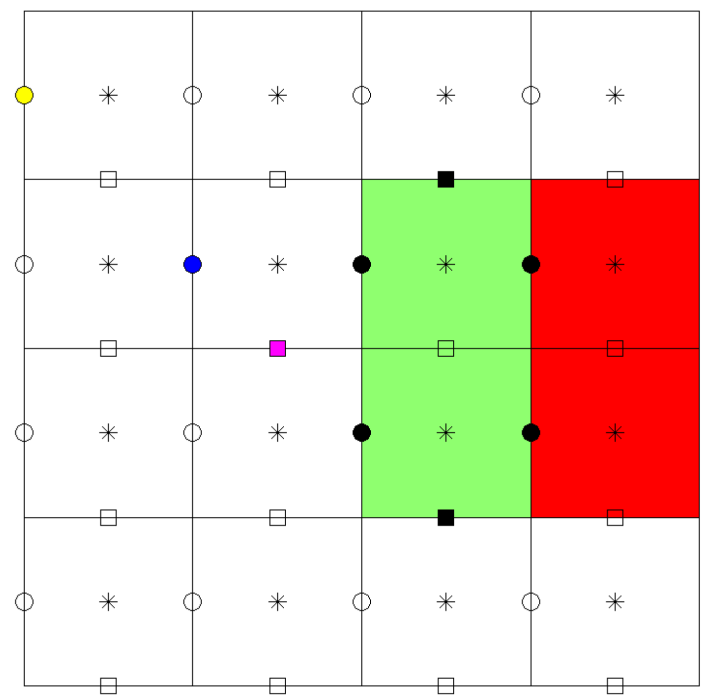
$$
\begin{aligned}
-\mu\Delta\mathbf{u} + \nabla(p+dz) + K^{-1}\mathbf{u} &= 0 \text{ in } \Omega\setminus G,\\
\nabla\cdot\mathbf{u} &= 0 \text{ in } \Omega\setminus G,\\
\mathbf{u}(x+il_x, y+jl_y, z+kl_z) &= \mathbf{u}(x,y,z) \text{ for } i,j,k\in\mathbb{Z}\\
p(x+il_x, y+jl_y, z+kl_z) &= p(x,y,z) \text{ for } i,j,k\in\mathbb{Z}\\
\mathbf{u} &= 0 \text{ on solid surface } \partial G
\end{aligned}
$$

$$
\begin{aligned}
G &= \text{solid cells (green or blue)}\\
\mu &= \text{viscosity},\\
\mathbf{u} &= \text{velocity},\\
p &= \text{pressure}\\
K &= \text{permeability} = \begin{cases}\begin{bmatrix}\infty & 0 & 0\\ 0 & \infty & 0\\ 0 & 0 & \infty\end{bmatrix} & \text{in empty cells}\\[2ex] \begin{bmatrix}\kappa_c & 0 & 0\\ 0 & \kappa_c & 0\\ 0 & 0 & \kappa_c\end{bmatrix} & \text{in red (c=1) or yellow (c=2) cells,}\end{cases}
\end{aligned}
$$



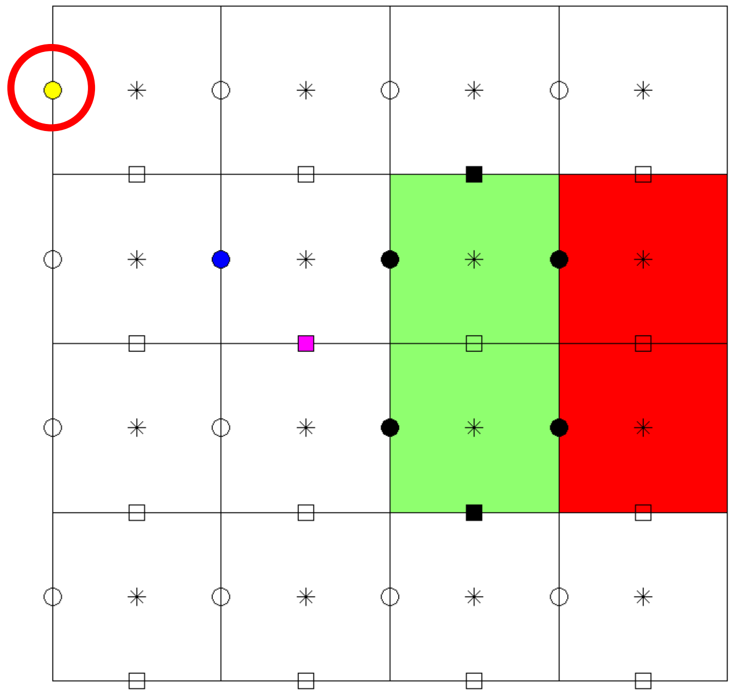
Stokes-Brinkmann on the staggered (MAC) grid

Green	solid cells
Red	permeable cells
Empty	empty cells
Circles	horizontal component of velocity
Squares	vertical component of velocity
Stars	pressure
Solid black	set variable to zero
Yellow	periodic boundary condition
Blue	no-slip on green in normal direction
Magenta	no-slip tangential direction



$$
\begin{aligned}
-\mu\frac{U_{i-1,k}+U_{i,k-1}-4U_{i,k}+U_{i+1,k}+U_{i,k+1}}{h^2}+\frac{P_{i,k}-P_{i-1,k}}{h}+\left(\frac{\kappa_{i-1,k}^{-1}+\kappa_{i,k}^{-1}}{2}\right)^{-1}U_{i,k} &= 0,\\
-\mu\frac{W_{i-1,k}+W_{i,k-1}-4W_{i,k}+W_{i+1,k}+W_{i,k+1}}{h^2}+\frac{P_{i,k}-P_{i,k-1}}{h}+\left(\frac{\kappa_{i,k-1}^{-1}+\kappa_{i,k}^{-1}}{2}\right)^{-1}W_{i,k} &= -d,\\
\frac{U_{i+1,k}-U_{i,k}}{h}+\frac{W_{i,k+1}-W_{i,k}}{h} &= 0.
\end{aligned}
$$

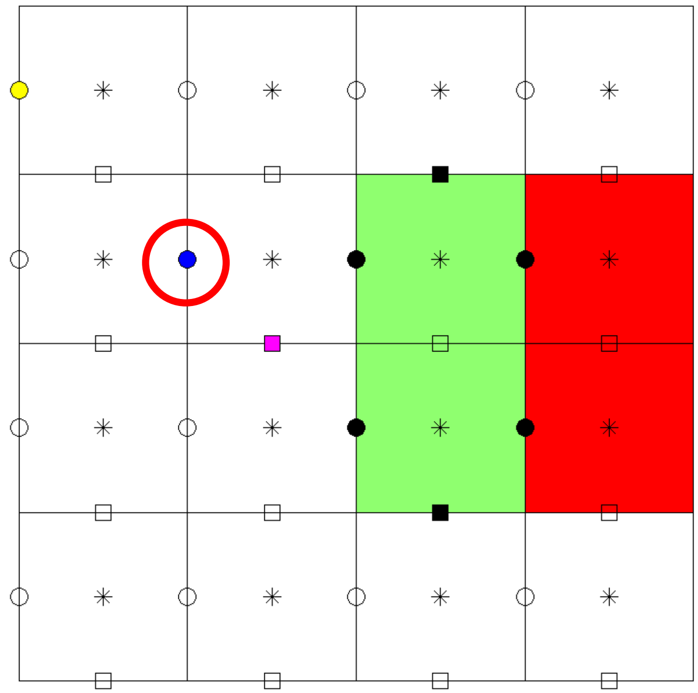
Periodic Boundary Conditions



$$
\begin{aligned}
\frac{U_{2,4}-U_{1,4}}{h}+\frac{W_{1,5}-W_{1,4}}{h} &= \\
\frac{U_{2,4}-U_{1,4}}{h}+\frac{W_{1,0}-W_{1,4}}{h} &= 0
\end{aligned}
$$

$$
\begin{aligned}
-\mu\frac{U_{0,4}+U_{1,3}-4U_{1,4}+U_{2,4}+U_{1,5}}{h^2}+\frac{P_{1,4}-P_{0,4}}{h} &= \\
-\mu\frac{U_{4,4}+U_{1,3}-4U_{1,4}+U_{2,4}+U_{1,1}}{h^2}+\frac{P_{1,4}-P_{4,4}}{h} &= 0
\end{aligned}
$$

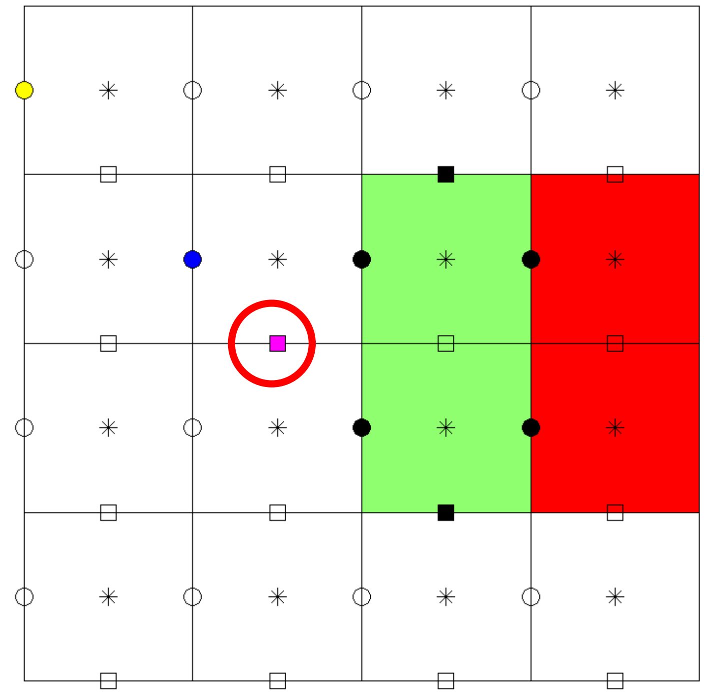
No-slip Boundary Conditions in the normal direction



$$\begin{aligned}
\frac{\cancelto{0}{U_{3,3}} - U_{2,3}}{h} + \frac{W_{2,4} - W_{2,3}}{h} &= \\
\frac{-U_{2,3}}{h} + \frac{W_{2,4} - W_{2,3}}{h} &= 0
\end{aligned}$$

$$\begin{aligned}
-\mu \frac{U_{1,3} + U_{2,2} - 4U_{2,3} + \cancelto{0}{U_{3,3}} + U_{2,4}}{h^2} + \frac{P_{2,3} - P_{1,3}}{h} &= \\
-\mu \frac{U_{1,3} + U_{2,2} - 4U_{2,3} \qquad + U_{2,4}}{h^2} + \frac{P_{2,3} - P_{1,3}}{h} &= 0.
\end{aligned}$$

No-slip in the tangential direction



$$
\begin{aligned}
-\mu \frac{W_{1,3} + W_{2,2} - 4W_{2,3} + \cancelto{-W_{2,3}}{W_{3,3}} + W_{2,4}}{h^2} + \frac{P_{2,3} - P_{2,2}}{h} &= \\
-\mu \frac{W_{1,3} + W_{2,2} - 5W_{2,3} \qquad + W_{2,4}}{h^2} + \frac{P_{2,3} - P_{2,2}}{h} &= -d.
\end{aligned}
$$

SIMPLE Method, part I

$$
\begin{aligned}
a^U_{i,k} U^*_{i,k} &= \Sigma a^U_{nb} U^*_{nb} + (P^*_{i-1,k} - P^*_{i,k}) A^U_{i,k} + b^U_{i,k} \\
a^W_{i,k} W^*_{i,k} &= \Sigma a^W_{nb} W^*_{nb} + (P^*_{i,k-1} - P^*_{i,k}) A^W_{i,k} + b^W_{i,k},
\end{aligned}
$$

$$
\begin{aligned}
P &= P^* + P' \\
U &= U^* + U' \\
V &= W^* + W'.
\end{aligned}
$$

$$
\begin{aligned}
a^U_{i,k} U'_{i,k} &= \Sigma a^U_{nb} U'_{nb} + (P'_{i-1,k} - P'_{i,k}) A^U_{i,k} \\
a^W_{i,k} W'_{i,k} &= \Sigma a^W_{nb} W'_{nb} + (P'_{i,k-1} - P'_{i,k}) A^W_{i,k}.
\end{aligned}
$$

$$
\begin{aligned}
U'_{i,k} &= (P'_{i-1,k} - P'_{i,k}) \frac{A^U_{i,k}}{a^U_{i,k}} \\
W'_{i,k} &= (P'_{i,k-1} - P'_{i,k}) \frac{A^W_{i,k}}{a^W_{i,k}}.
\end{aligned}
$$

SIMPLE Method, part II

$$
\begin{aligned}
U_{i,k} &= U^*_{i,k} + (P'_{i-1,k} - P'_{i,k})\frac{A^U_{i,k}}{a^U_{i,k}} \\
W_{i,k} &= W^*_{i,k} + (P'_{i,k-1} - P'_{i,k})\frac{A^W_{i,k}}{a^W_{i,k}},
\end{aligned}
$$

$$
\begin{aligned}
U_{i+1,k} &= U^*_{i+1,k} + (P'_{i,k} - P'_{i+1,k})\frac{A^U_{i+1,k}}{a^U_{i+1,k}} \\
W_{i,k+1} &= W^*_{i,k+1} + (P'_{i,k} - P'_{i,k+1})\frac{A^W_{i,k+1}}{a^W_{i,k+1}}.
\end{aligned}
$$

$$
a^P_{i,k}P'_{i,k} = a^P_{i+1,k}P'_{i+1,k} + a^P_{i-1,k}P'_{i-1,k} + a^P_{i,k+1}P'_{i,k+1} + a^P_{i,k-1}P'_{i,k-1} + b^P_{i,k},
$$

$$
\begin{aligned}
b^P_{i,k} &= U'_{i+1,k} - U'_{i,k} + W'_{i,k+1} - W'_{i,k}, \\
a^P_{i,k} &= a^P_{i+1,k} + a^P_{i-1,k} + a^P_{i,k+1} + a^P_{i,k-1}.
\end{aligned}
$$

Pressure Drop Optimization by Chen et al.[1]

[1]Chen, Pui and Liu, *Aerosol Science and Technology*, 1995

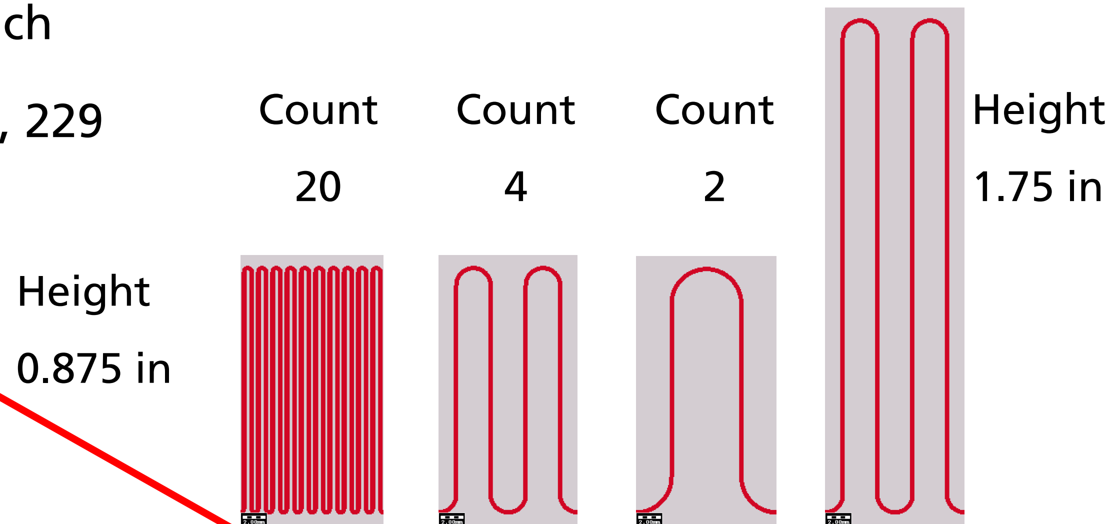
Pleat **heights**: 0.875, 1.75, 3.5 and 5.25 inch

Pleat **counts**: 2, 3, 4,…, 20 pleats / inch

Pleat **media**: 252, 213, 233, 220, 224, 229

Grid resolution: 8 μm ~ 5 cells

Domains: from 16 x 1 x 303 cells
to 158 x 1 x 1692 cells



Grade no.	DOP Efficiency	Permeability [m²]	Thickness	Base weight
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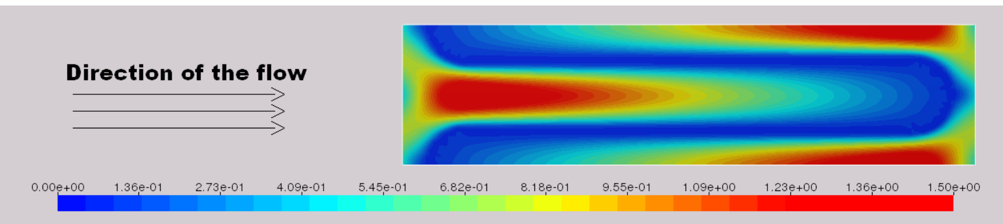
233	98.5 %	2.26e-12	0.38	73
220	95 %	3.20e-12	0.38	73
224	90-95% ASHRAE	7.67e-12	0.38	73
229	80-90 % ASHRAE	1.10e-11	0.38	73

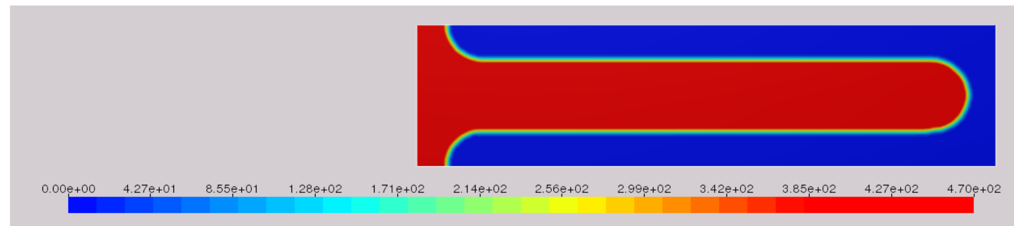
Magnitude of Velocity and Pressure Drop for varying inlet length

- Velocity: 100 fpm (0.508 m/s)
- Pressure in Pascal

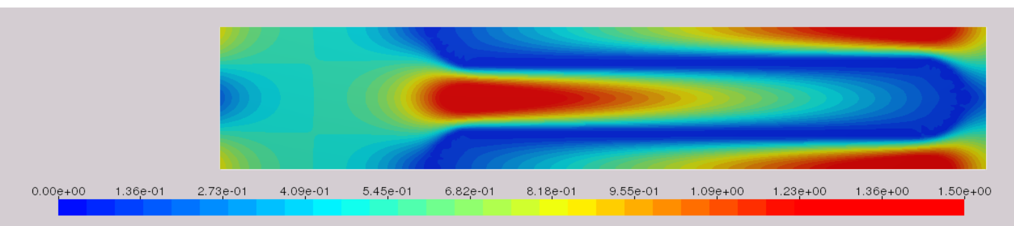
- air at 20°C.
  density 1.2 kg/m³
  viscosity 1.5e-5 m²/s

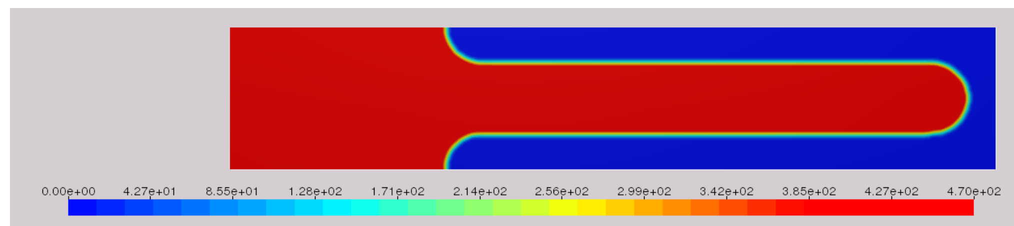
- Media 213
  Height 0.875 in
  Pleat count 4 / in



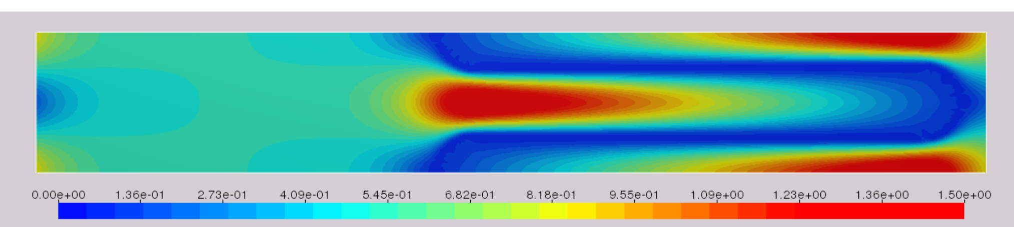


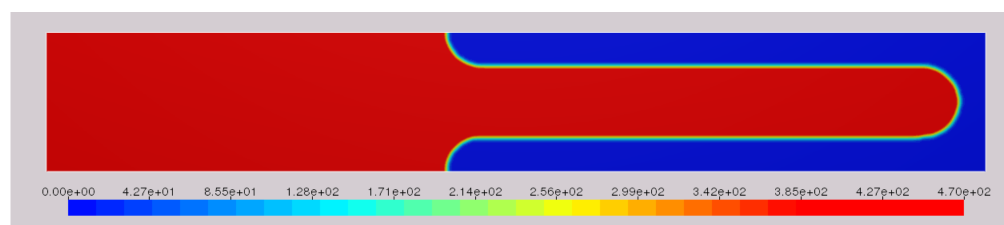
Magnitude of velocity   Inlet 1 mm   Pressure





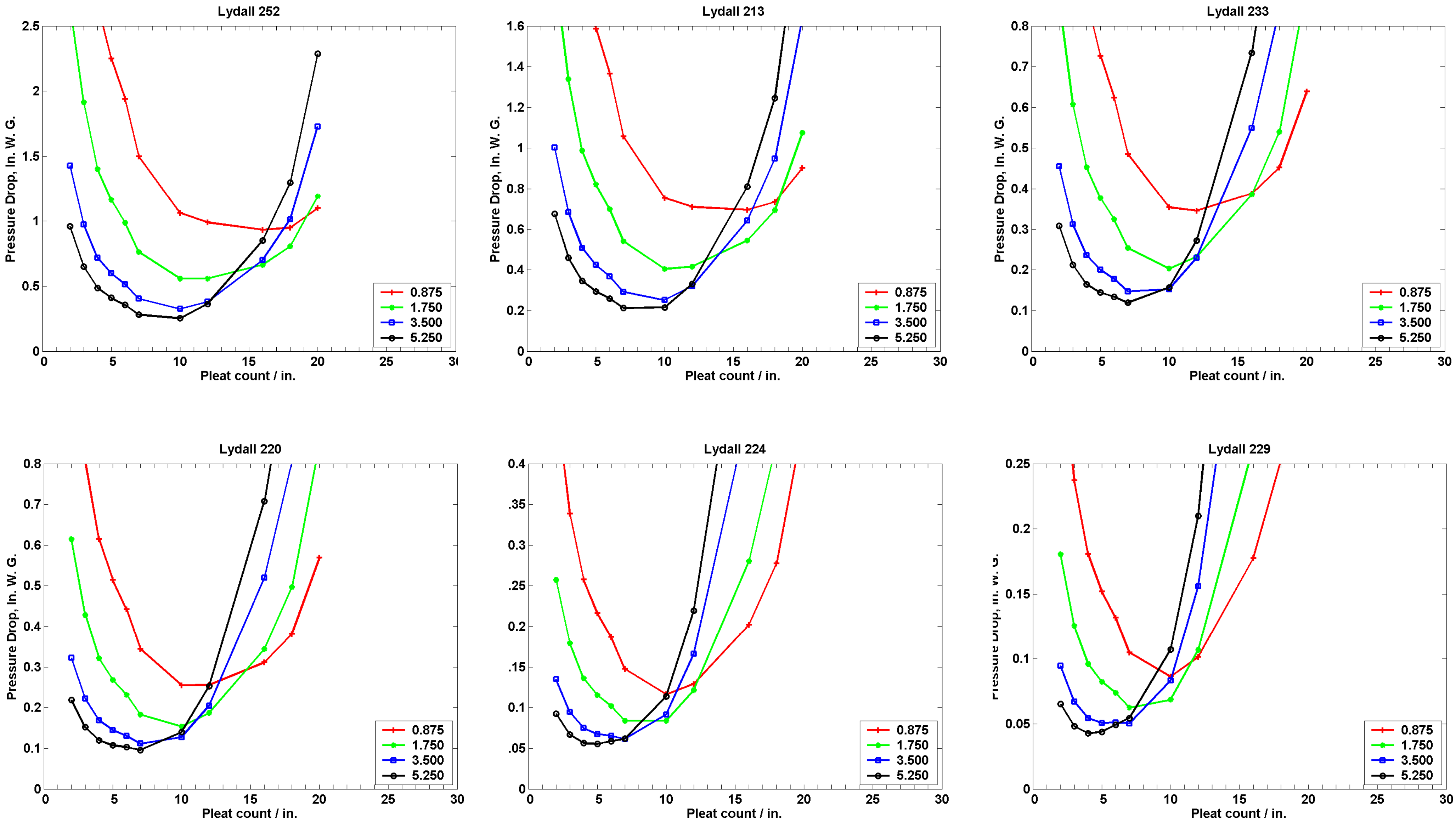
Magnitude of velocity   Inlet 9 mm   Pressure



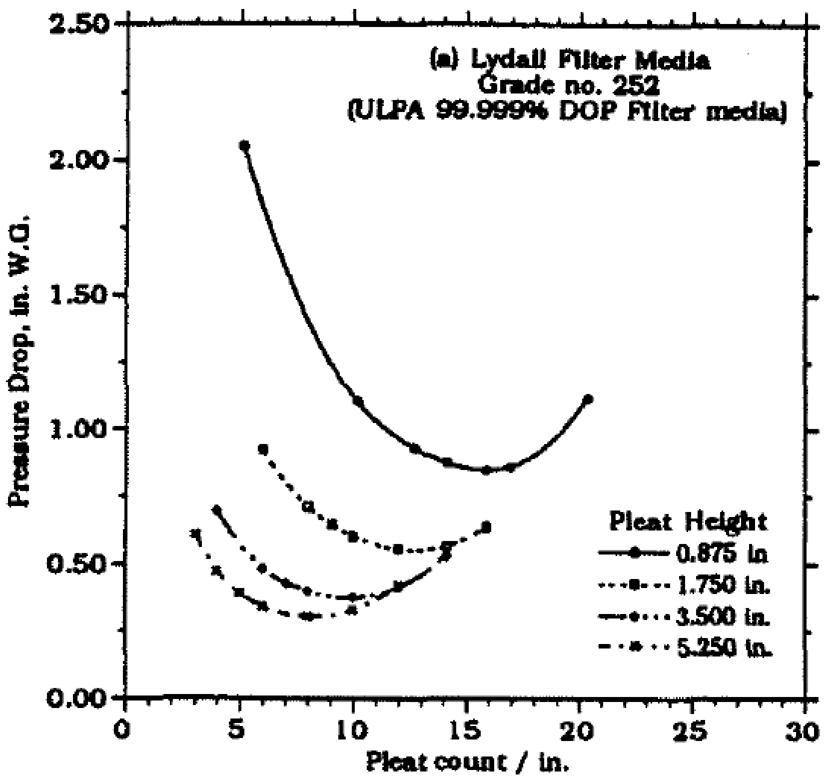


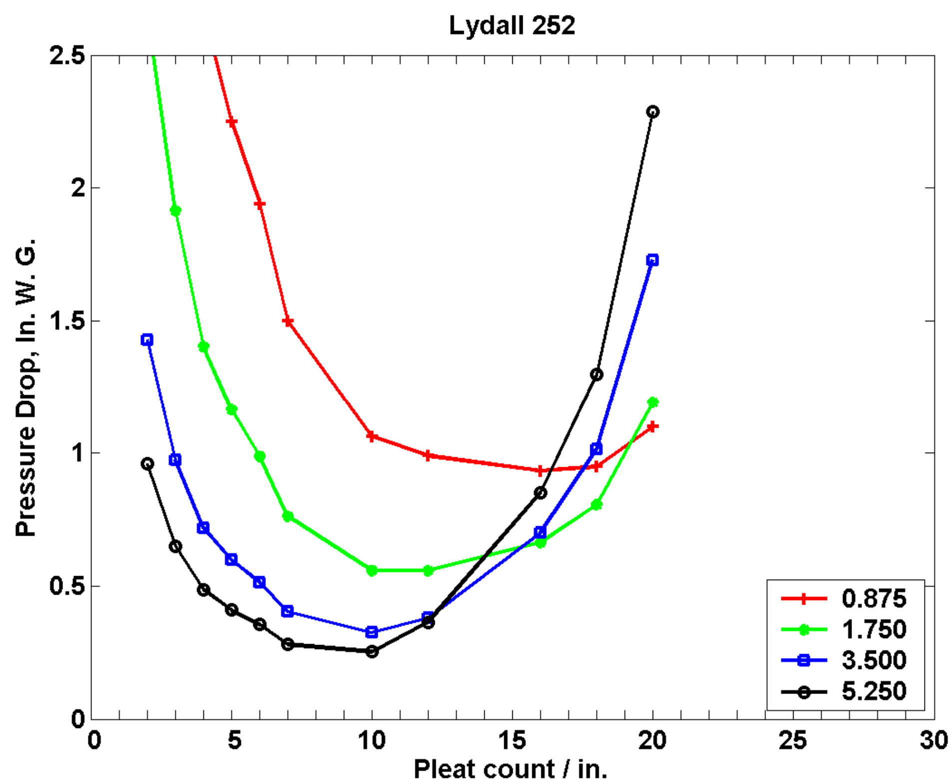
Magnitude of velocity   Inlet 17 mm   Pressure

Pressure drop for 6 media, different heights and pleat counts



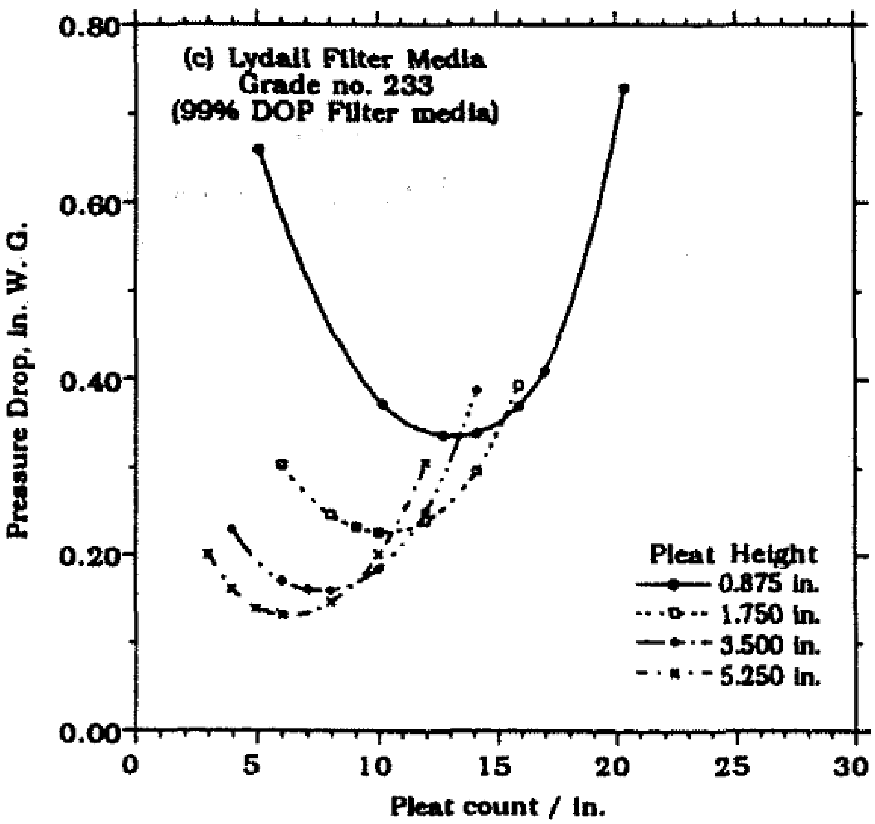
Lydall Grade no. 252 compared with Chen at al.

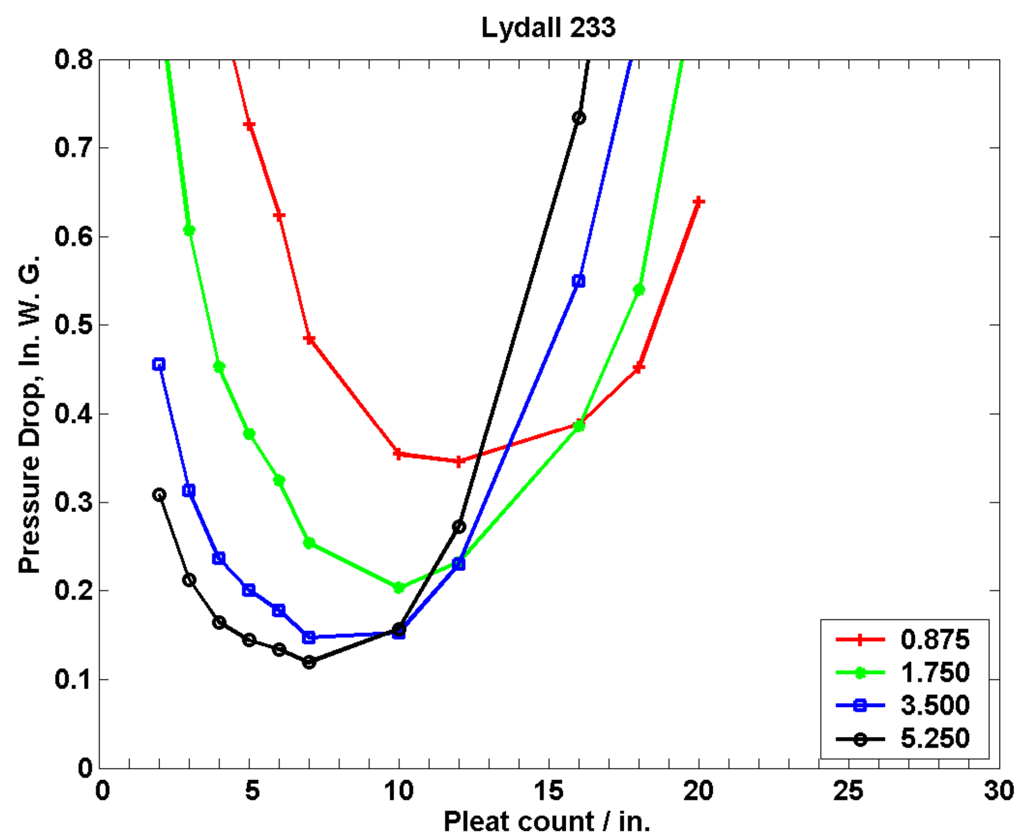




- Great quantitative agreement
- For low pleat count, high pleat is better
- For high pleat count, low pleat is better

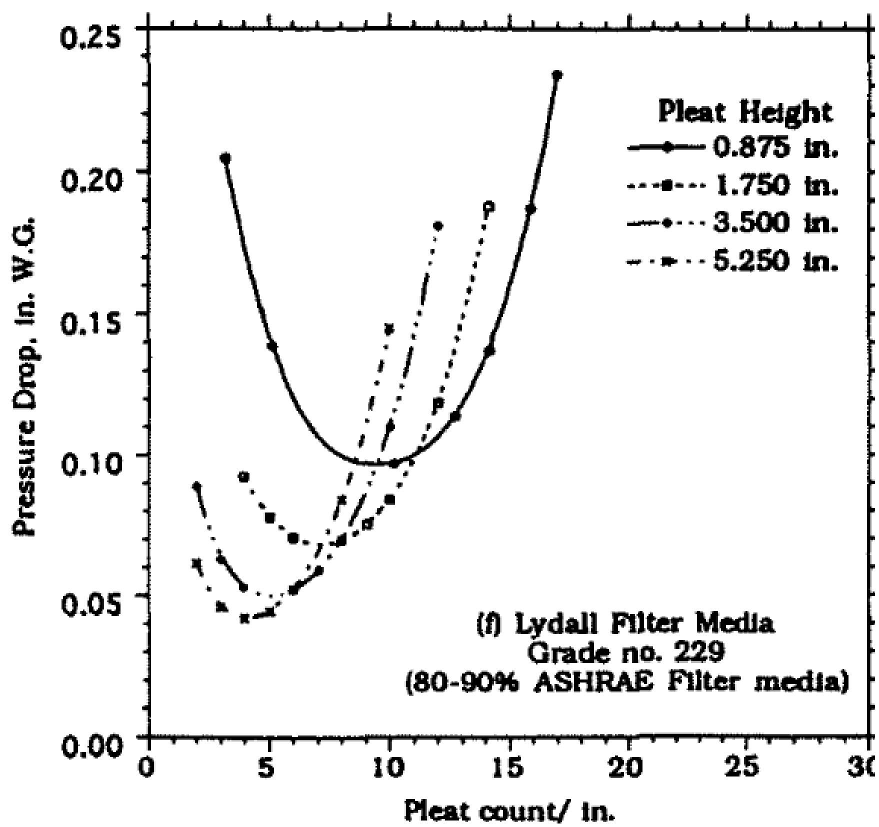
Lydall Grade no. 233 compared with Chen at al.

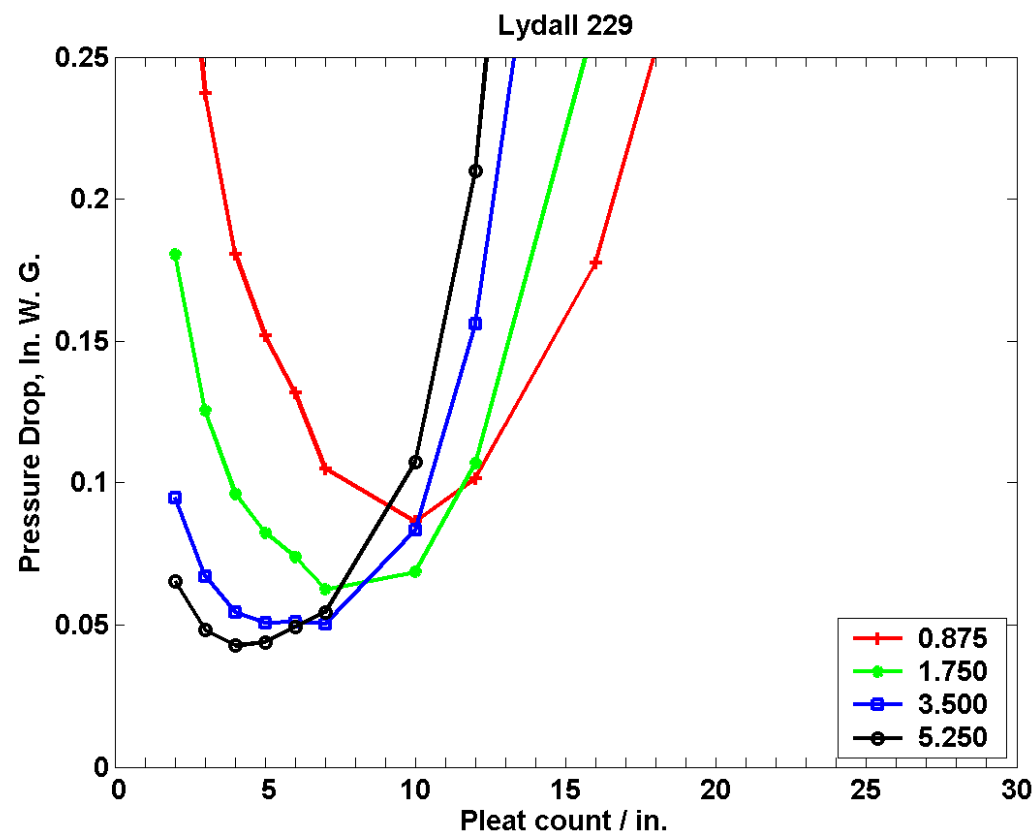




- Great quantitative agreement
- For low pleat count, high pleat is better
- For high pleat count, low pleat is better

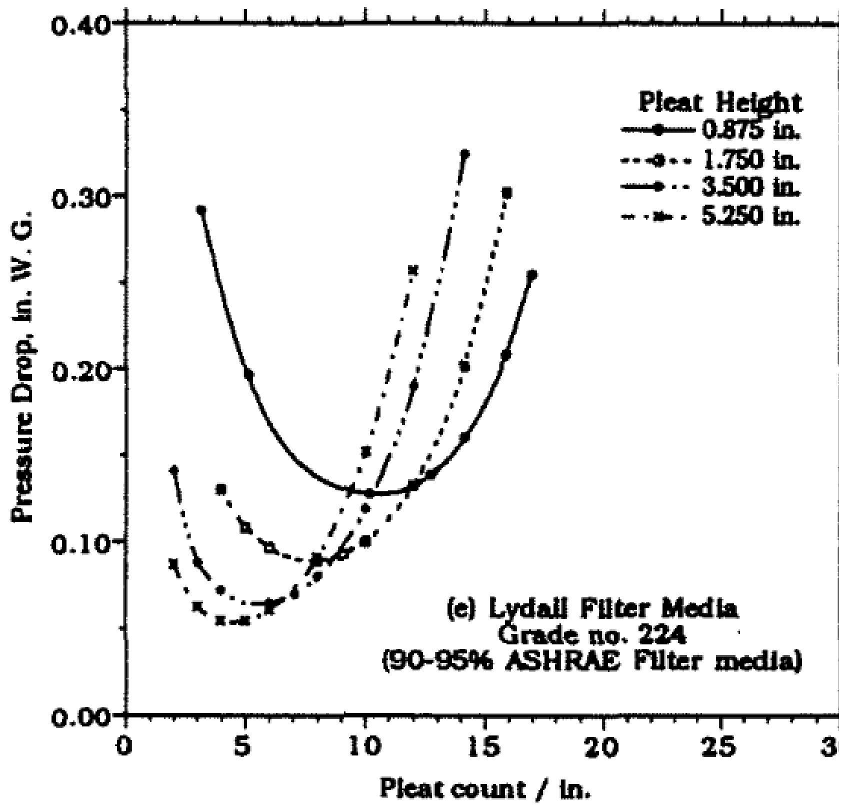
Lydall Grade no. 229 compared with Chen at al.

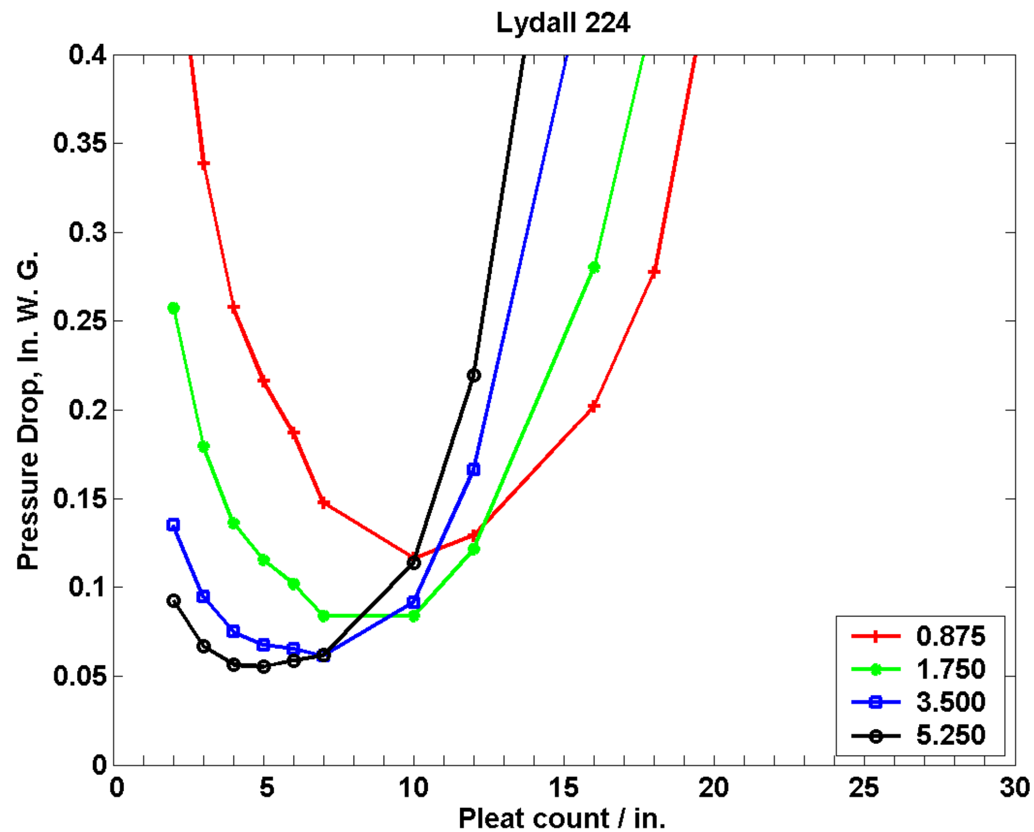




- Great quantitative agreement
- For low pleat count, high pleat is better
- For high pleat count, low pleat is better

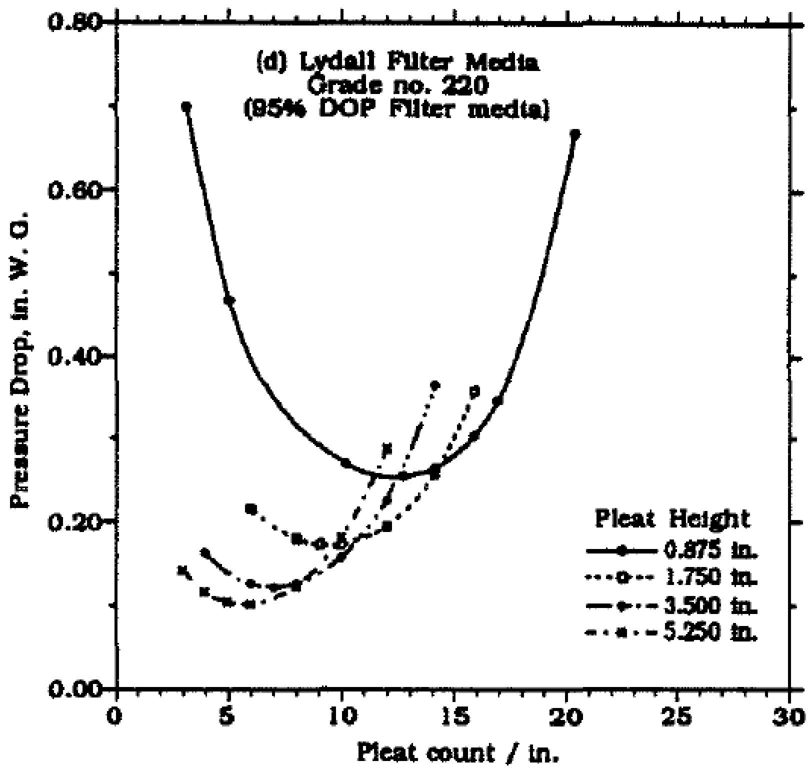
Lydall Grade no. 224 compared with Chen at al.

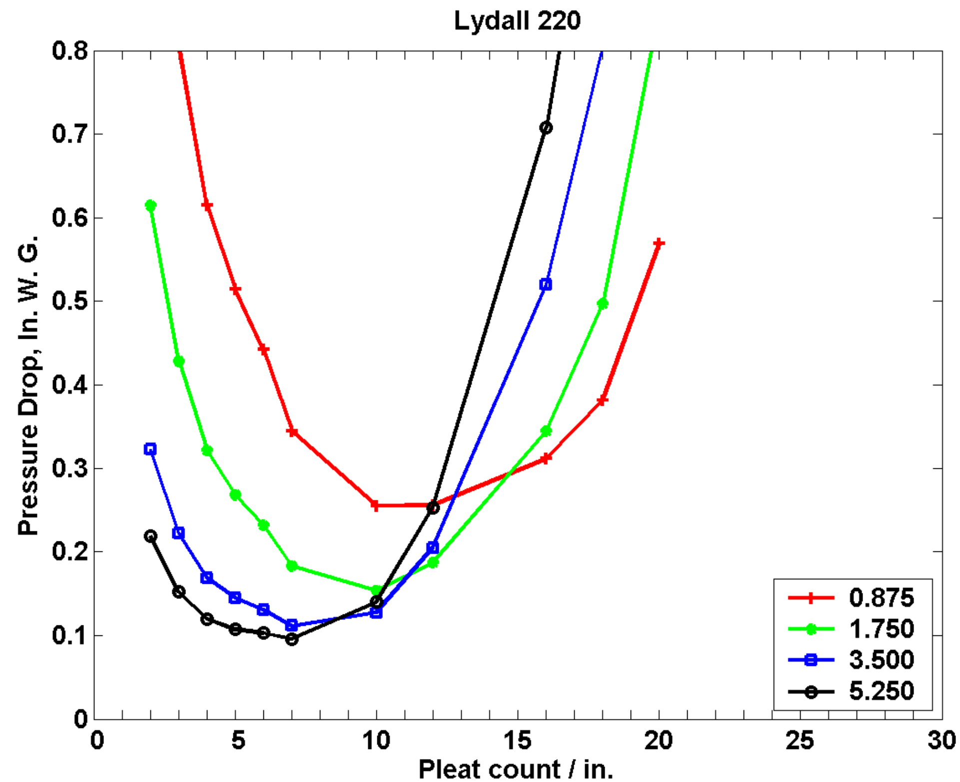




- Great quantitative agreement
- For low pleat count, high pleat is better
- For high pleat count, low pleat is better

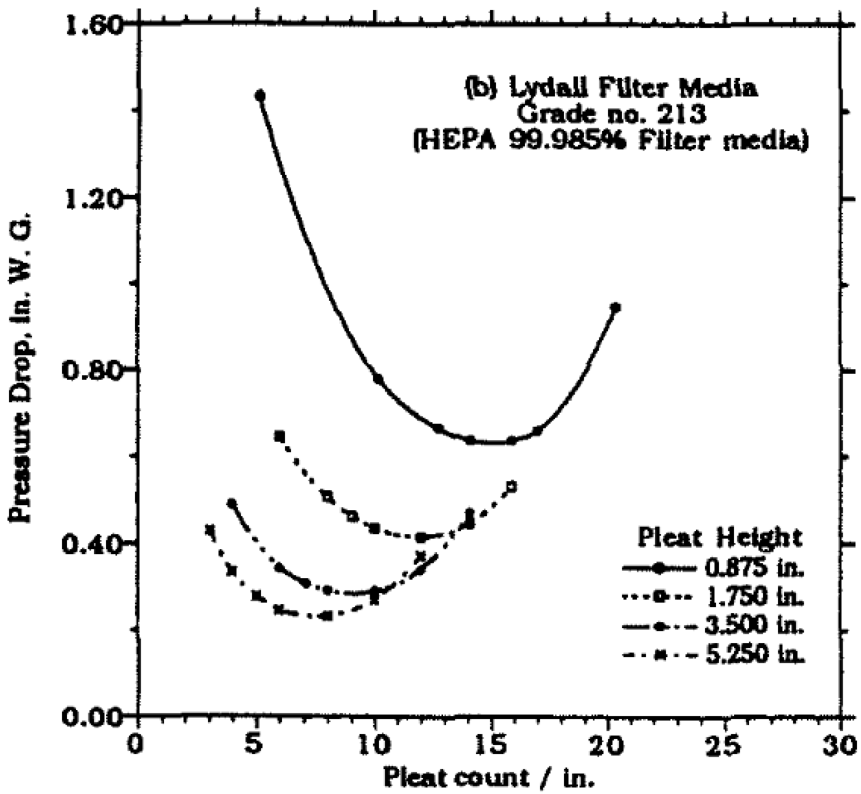
Lydall Grade no. 220 compared with Chen at al.

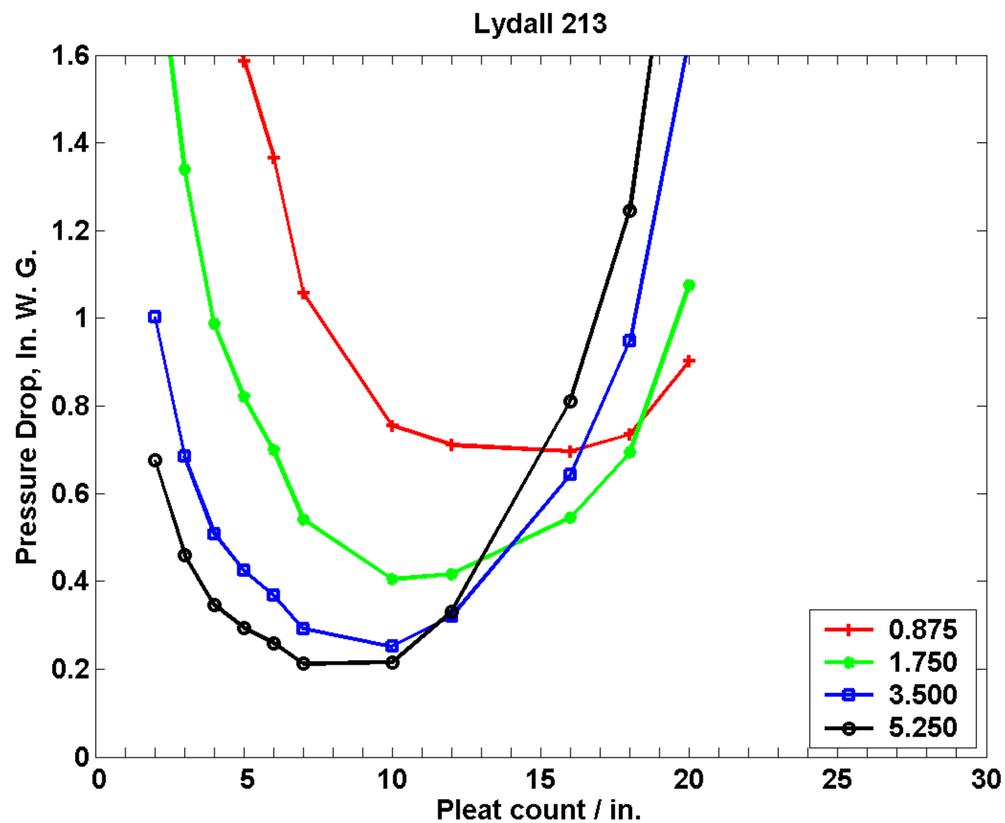




- Great quantitative agreement
- For low pleat count, high pleat is better
- For high pleat count, low pleat is better

Lydall Grade no. 213 compared with Chen at al.





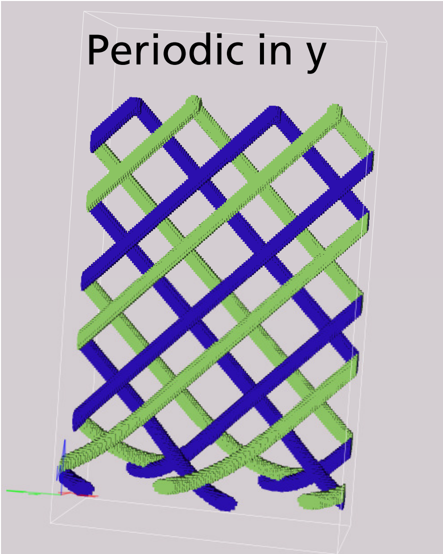
- Great quantitative agreement
- For low pleat count, high pleat is better
- For high pleat count, low pleat is better

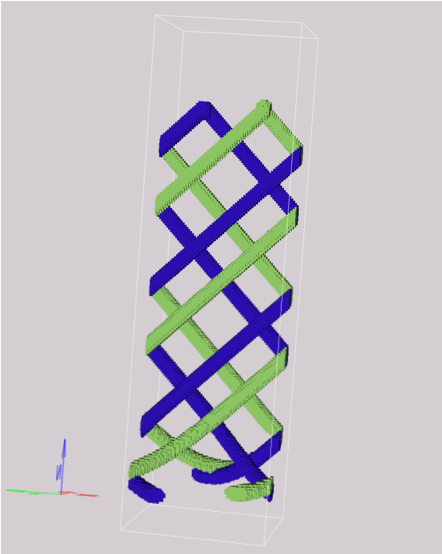
Validation of oil simulations.

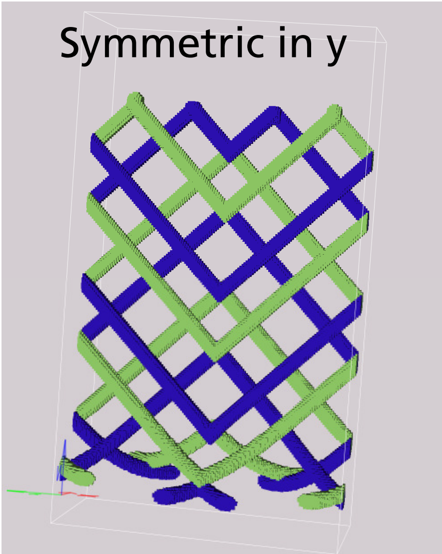
- Comparison with ITWM's SuFiS software:
  Deviation systematically 3 % lower than SuFiS.

- SuFiS is validated for many years in collaboration with IBS Filtran.
  See also *talk by Dr. Iliev*.

- Changing to symmetry boundary conditions (doubles the domain):
  Within 1 % of SuFiS value.

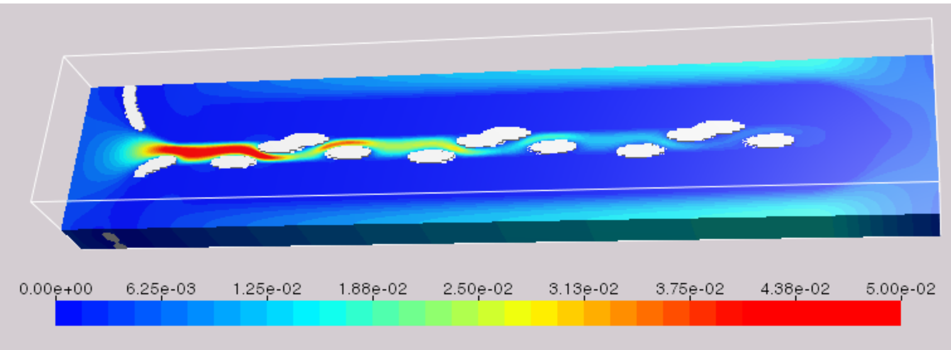




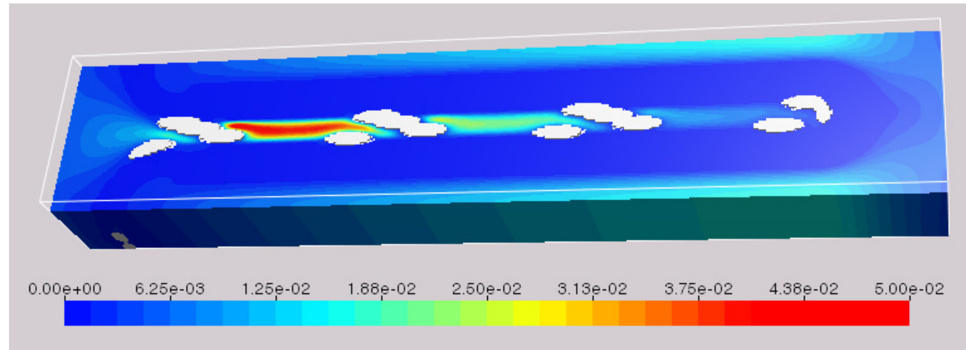


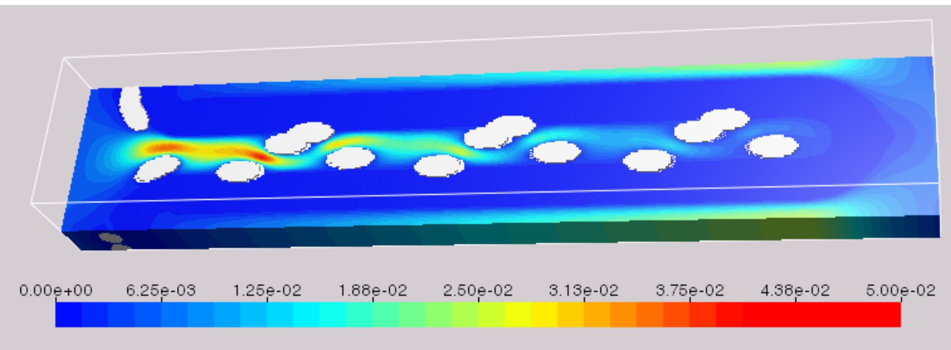
Oil flow in pleats with support structure: velocity

- Velocity: 0.15 m/s
- Oil: density 850 kg/m³ viscosity 0.17 m²/s
- Same pleat count
- Different in- and outflow channel widths
- Grid resolution 40 µm
- 50 x 70 x 380 cells

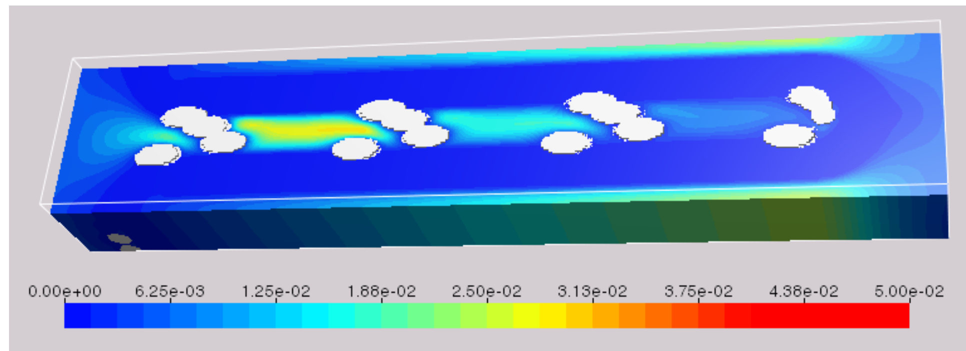


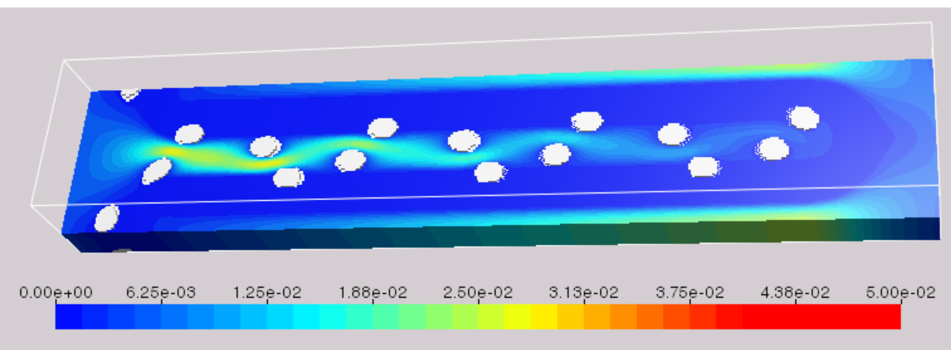
Narrow Channel



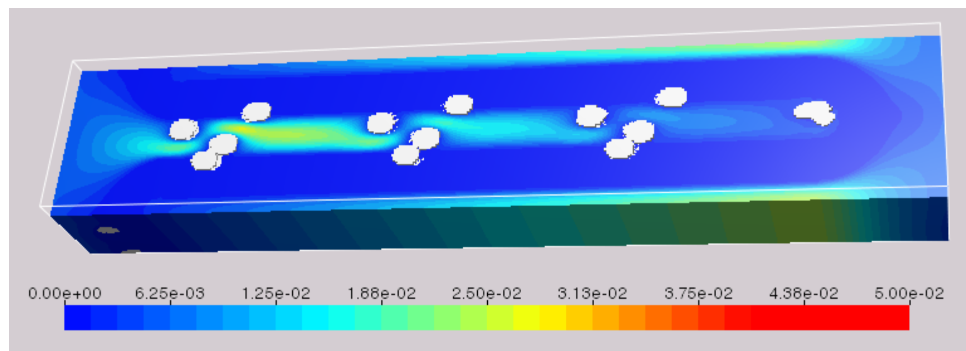


Thick Wire



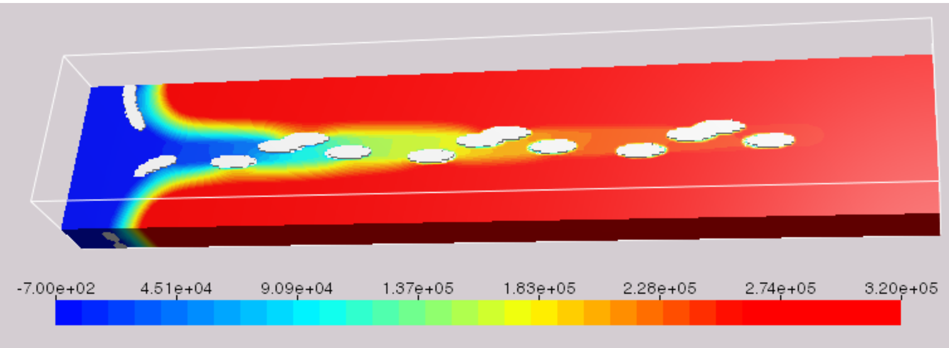


Thin Wire



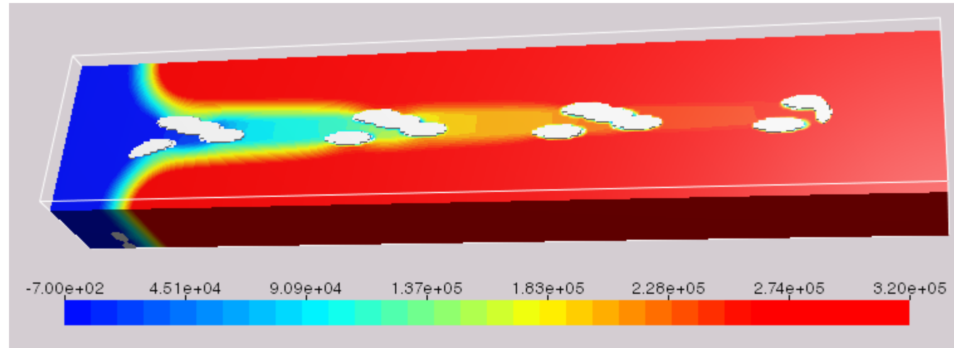
Oil flow in pleats with support structure: pressure

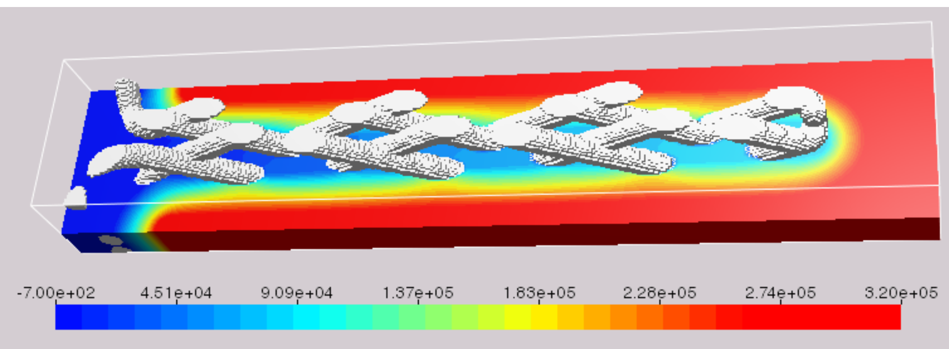
- Pressure in Pascal
- Oil: density 850 kg/m³ viscosity 0.17 m²/s
- Same pleat count
- Different in- and outflow channel widths
- Grid resolution 40 µm
- 50 x 70 x 380 cells



Narrow Channel:

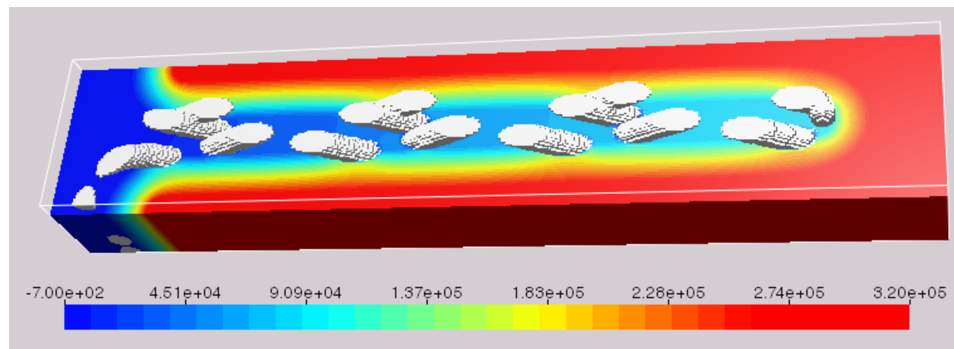
4 bar

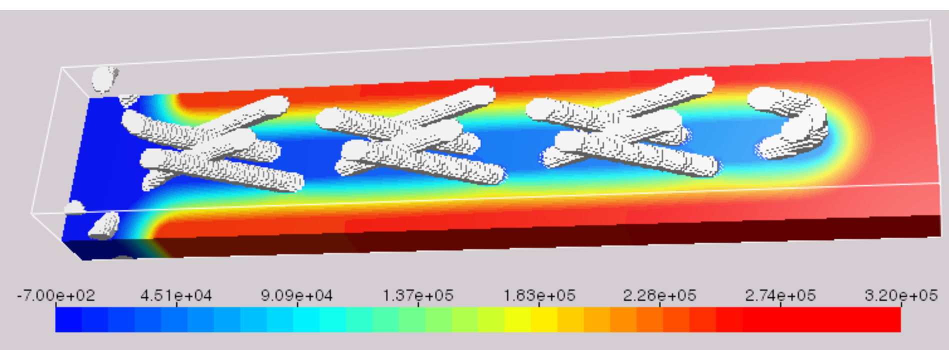




Thick Wire:

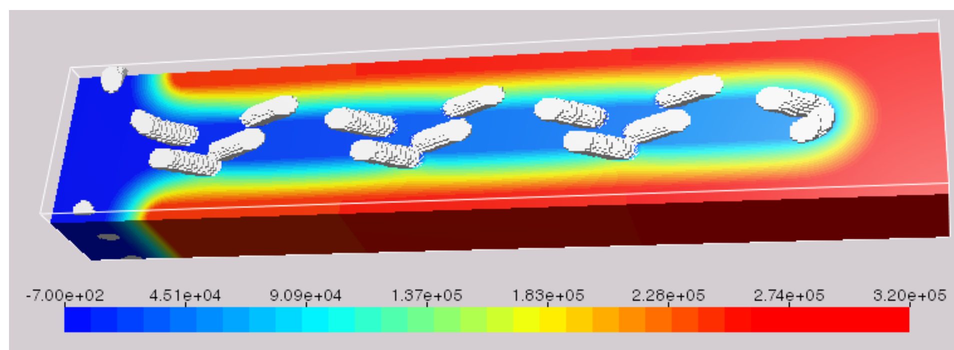
3.1 bar





Thin Wire:

2.7 bar



Conclusions and remarks

- Same experiments – same results as Chen, Pui & Lui, 1995: validation successful
- Different inlet length
- Periodic boundary conditions
- Stokes-Brinkmann equations
- Complete 2d air filtration study (6x4x14 runs) takes 1 day on 8 CPU desktop computer, 4 days on laptop

- No support: media **permeability**, media **surface area** and **channel width** matter
- With support: also **channel structure** and **occluded media surface** area matter
- Single 3d oil filtration computation takes 45 min on 8 CPU desktop computer, 4 hours on laptop.

- Evaluate Software at www.geodict.com

Pleat structures, pressure drop computations and figures made with our Software

GEO DICT

Thank you for your time and attention

www.geodict.com