A HIGH-EFFICIENCY MICRO CHANNEL REGENERATIVE HEAT EXCHANGER FOR FLUID PROCESSING

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Bellevue, WA

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OUTLINE

- On Intellectual Ventures: a sampling of R&D activities
- Micro-channel Heat Exchanger
  - Concept introduction
  - fluidic, thermal and structural analysis
  - Prototype assembly and testing
  - conclusions

Intellectual Ventures Laboratories

IV Main Lab Machine Shop– Bellevue, WA

Physics
Engineering
Food Science
Epidemiological modeling
Health technologies
and many more areas

Wide variety of projects

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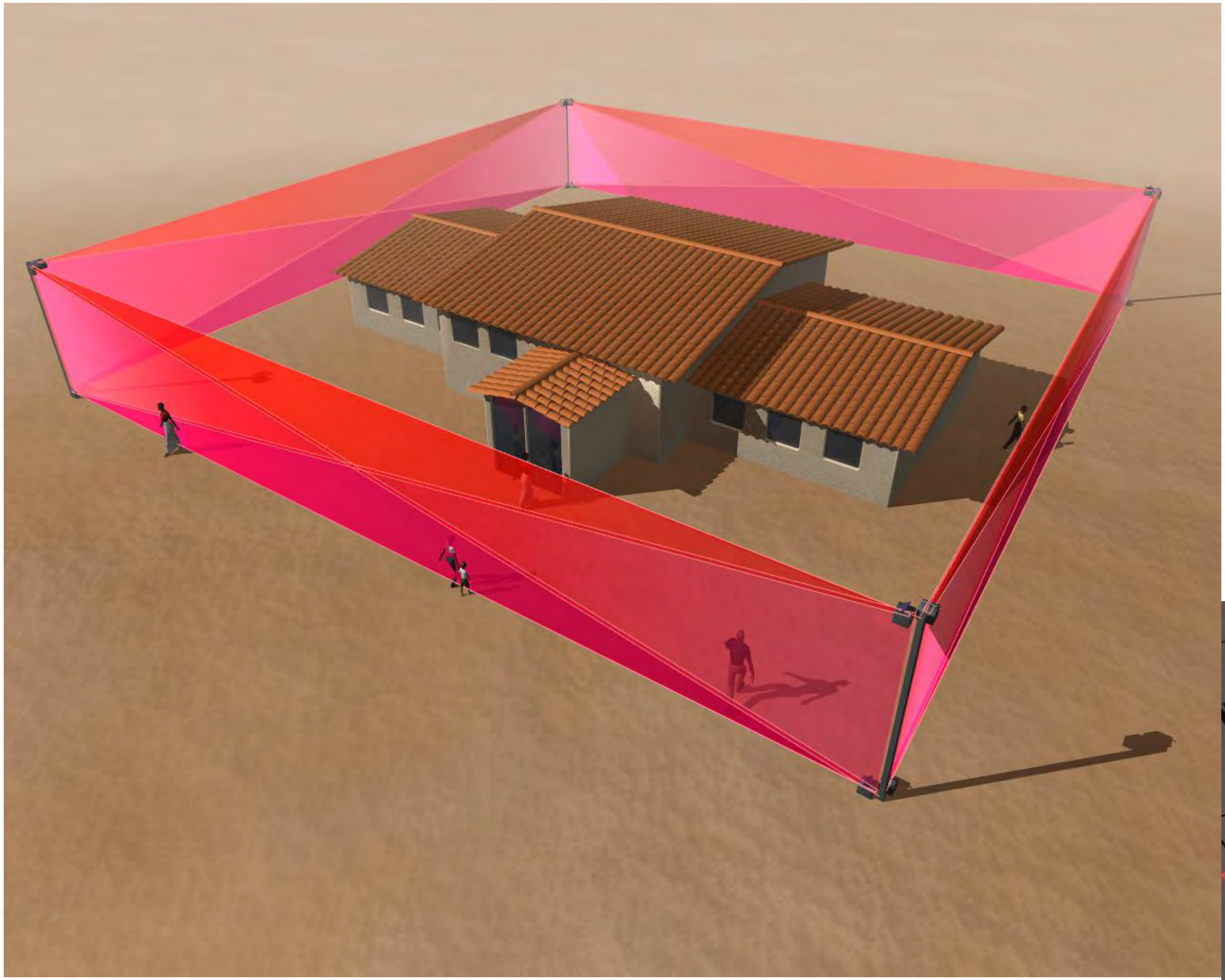
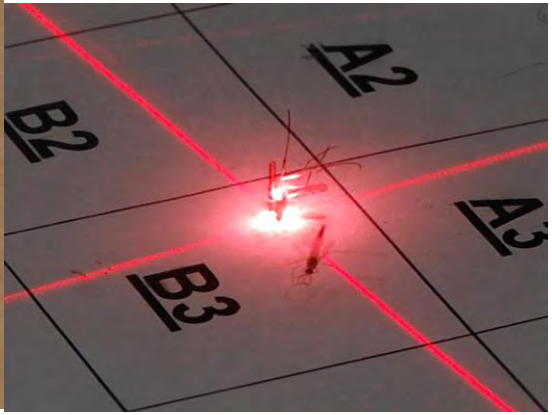
Photonic fence- *target & shoot mosquitos with lasers*





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Photonic fence- *target & shoot mosquitos with lasers*

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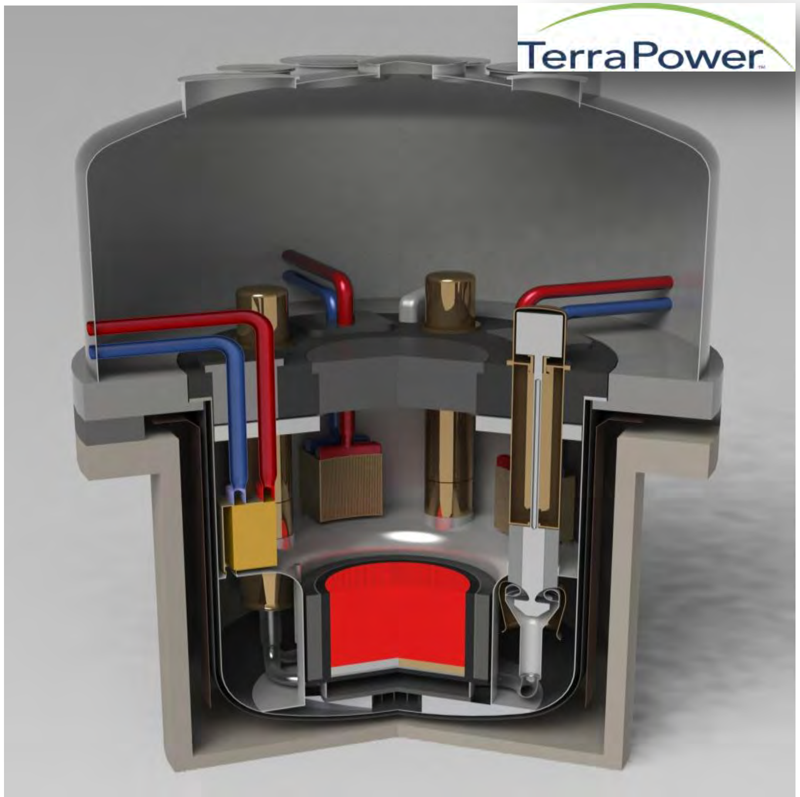
TerraPower nuclear reactor- *burn depleted Uranium fuel*

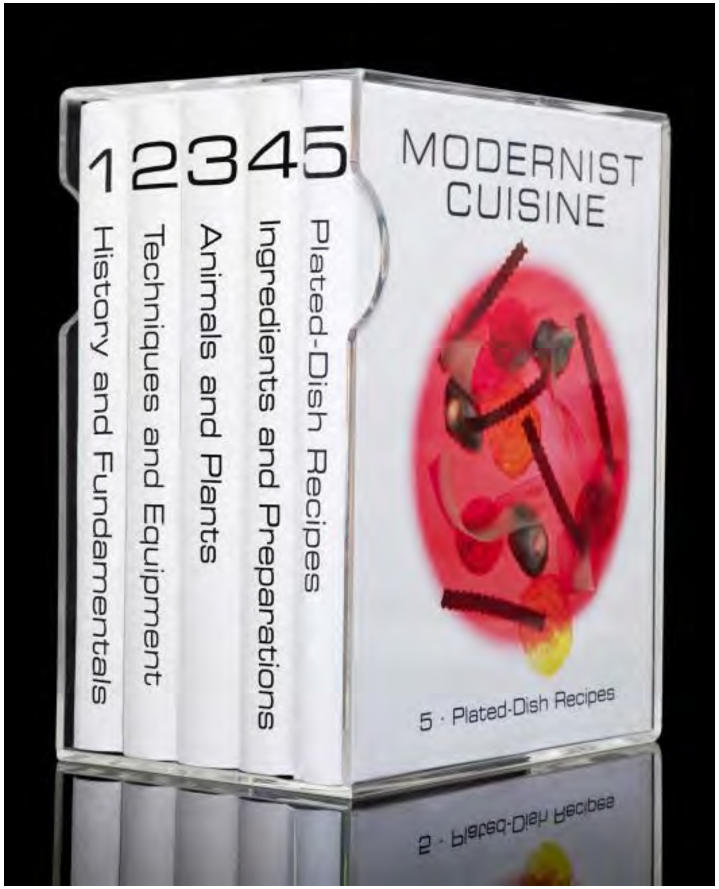


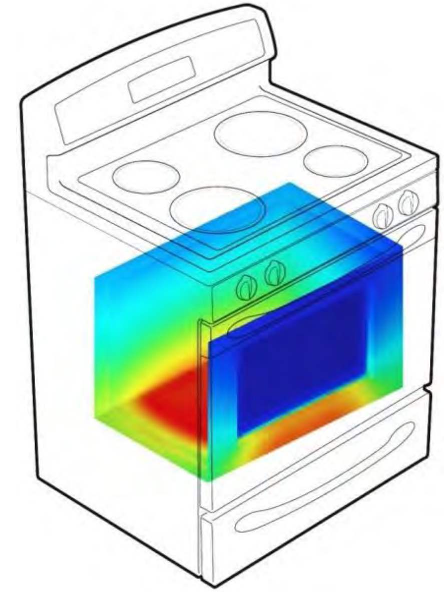
TerraPower Reactor Traveling-Wave Reactor

ColdChain- *Keep vaccines cold passively for months*

super insulated vaccine container

Modernist Cuisine project





Not your typical "cookbook"

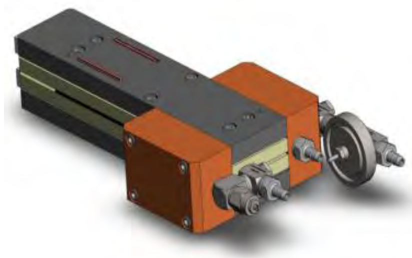
Lots of science, computer models and state of art photography to explain physics of food. And yes, recipes too.

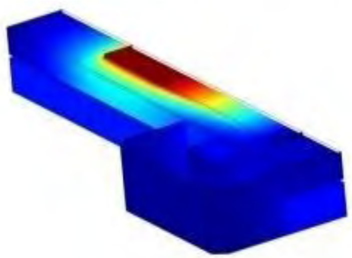
www.modernistcuisine.com

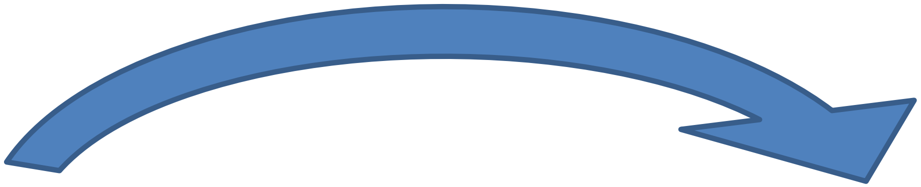
Micro-channel Heat Exchanger

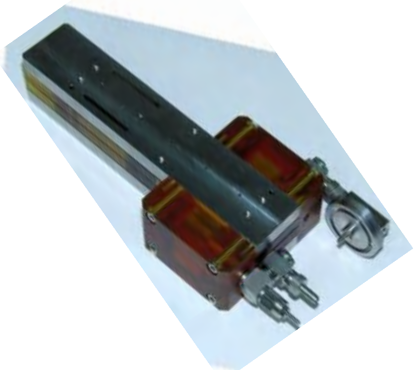
Micro-channel Heat Exchanger Development Process

CAD models









Computer models for understanding and design

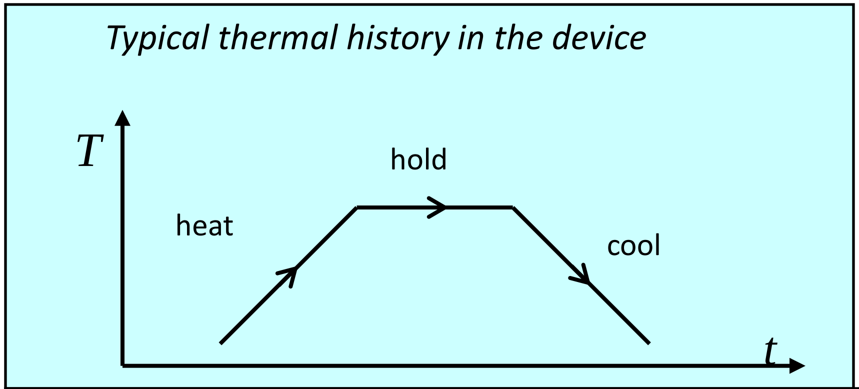
Physical model for testing and verification

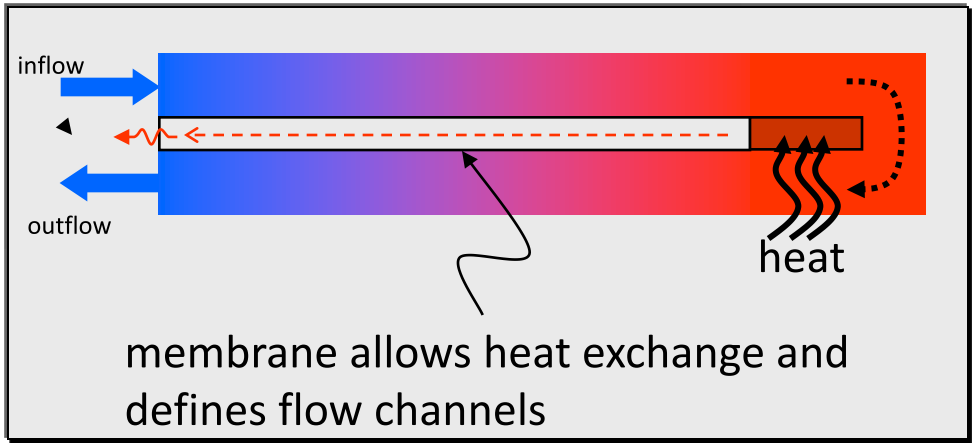
Specific design intended for **sterilization** of **water** or similar liquids.

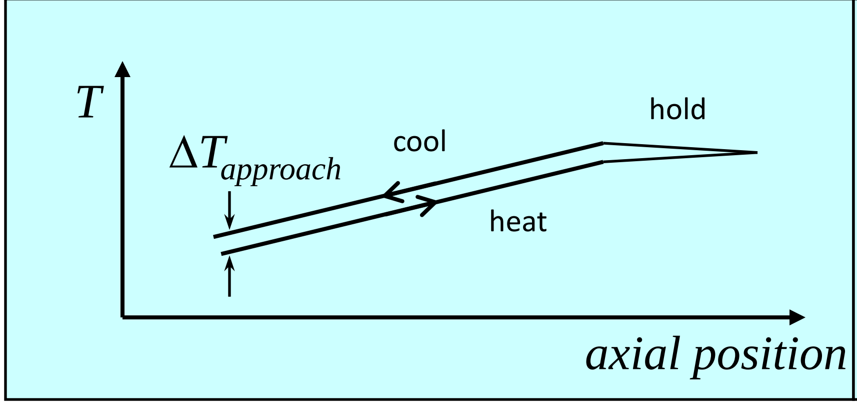
How it works

- applies thermal energy to a liquid
- then captures it back (→ regenerative)
- Achieves thermal cycling

- very efficient, low power consumption
- small
- modular (scalable)







To keep the device going, energy must be continuously supplied to make up for

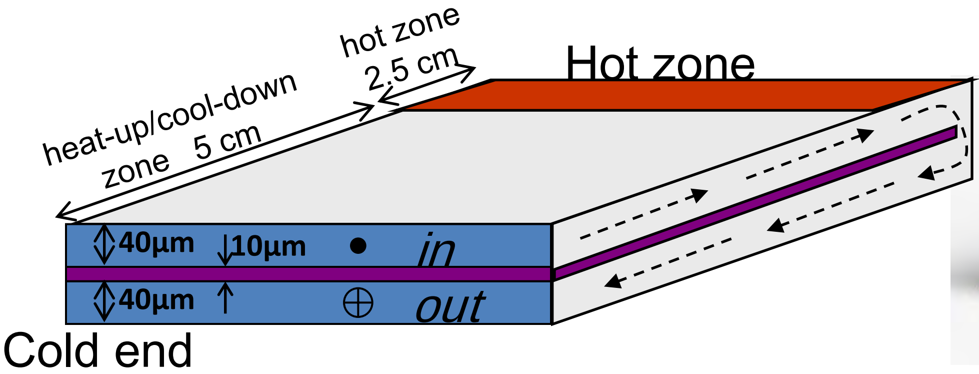
- $\Delta T_{approach}$
- other energy losses (heat to ambient, pumping etc)

$\Delta T_{approach}$ is a measure of heat recapture efficiency

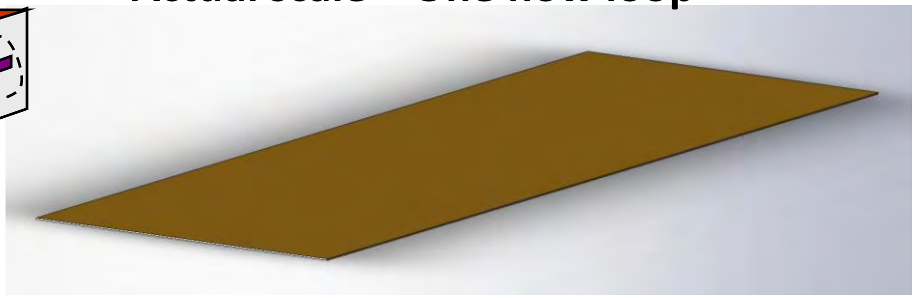
→ minimize $\Delta T_{approach}$

"Unit" flow loop and scalability

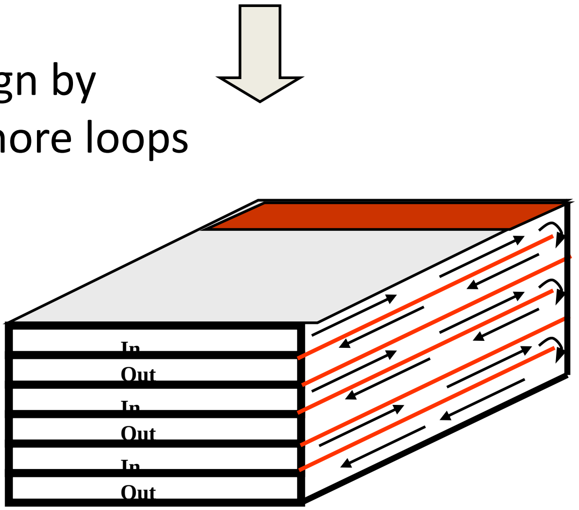
Schematic– One flow loop



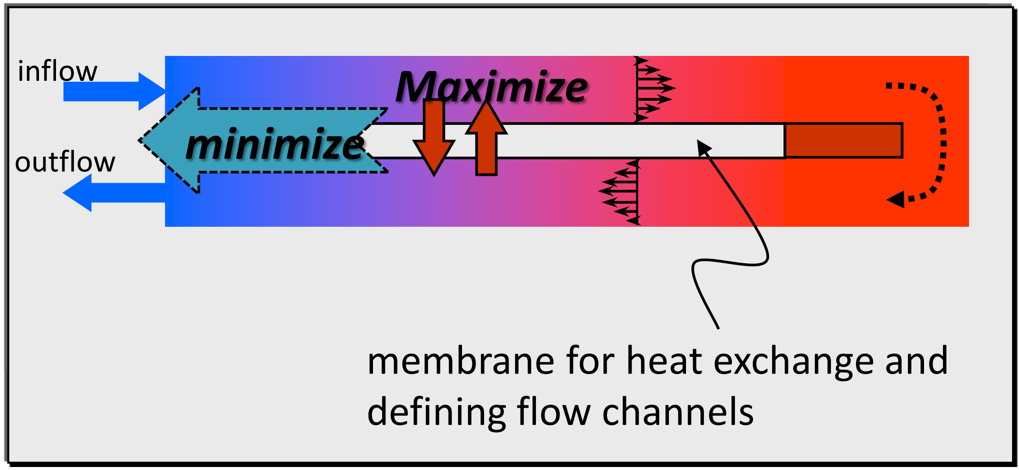
Actual scale – One flow loop



Scale design by stacking more loops



Fundamental heat transfer trade off



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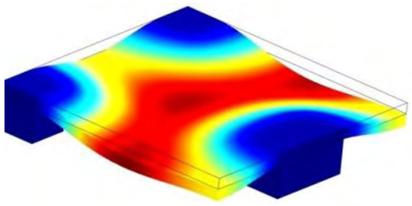
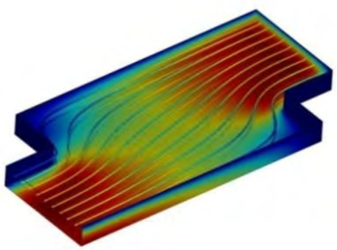
Analyses performed (multiple physics analyzed independently)

Thermal analysis → Regenerative efficiency

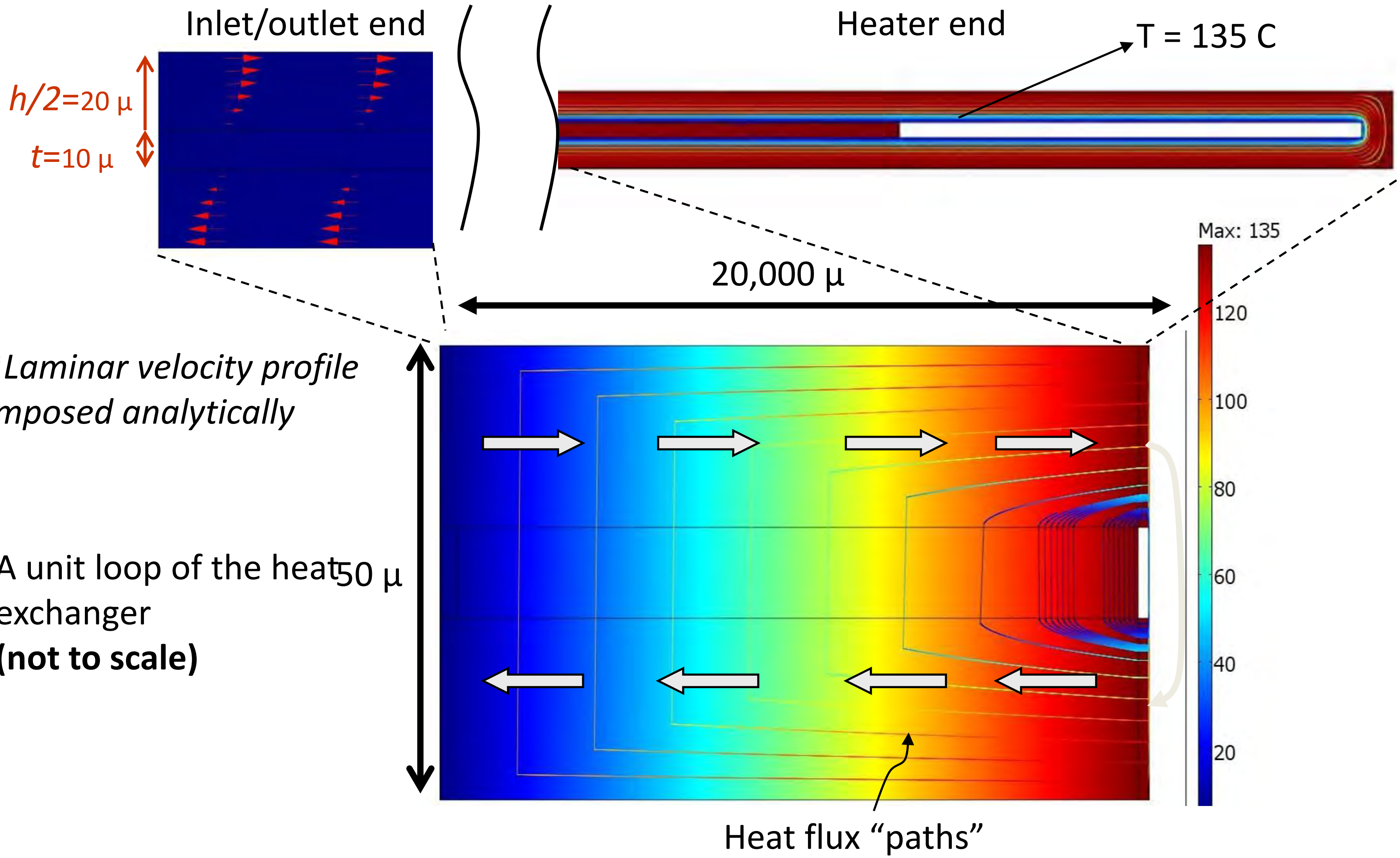
Structural analysis → Post design to prevent channel collapse



Fluid dynamics analysis → Pressure head loss & loading



2D thermal analysis with flow



**Laminar velocity profile imposed analytically*

A unit loop of the heat exchanger
(not to scale)

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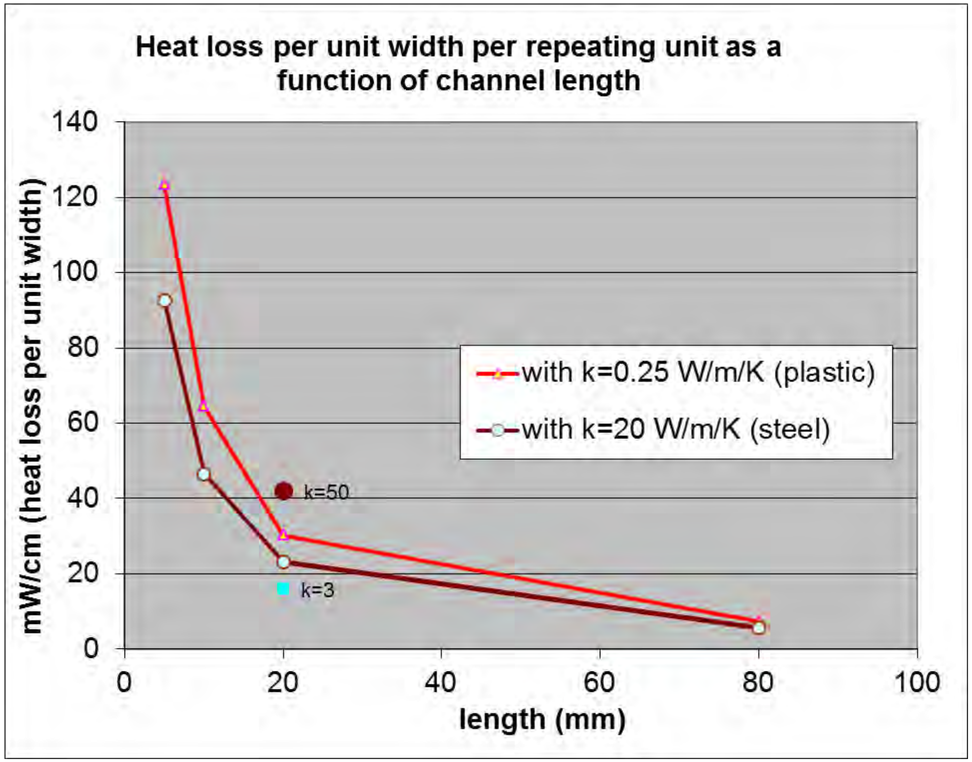
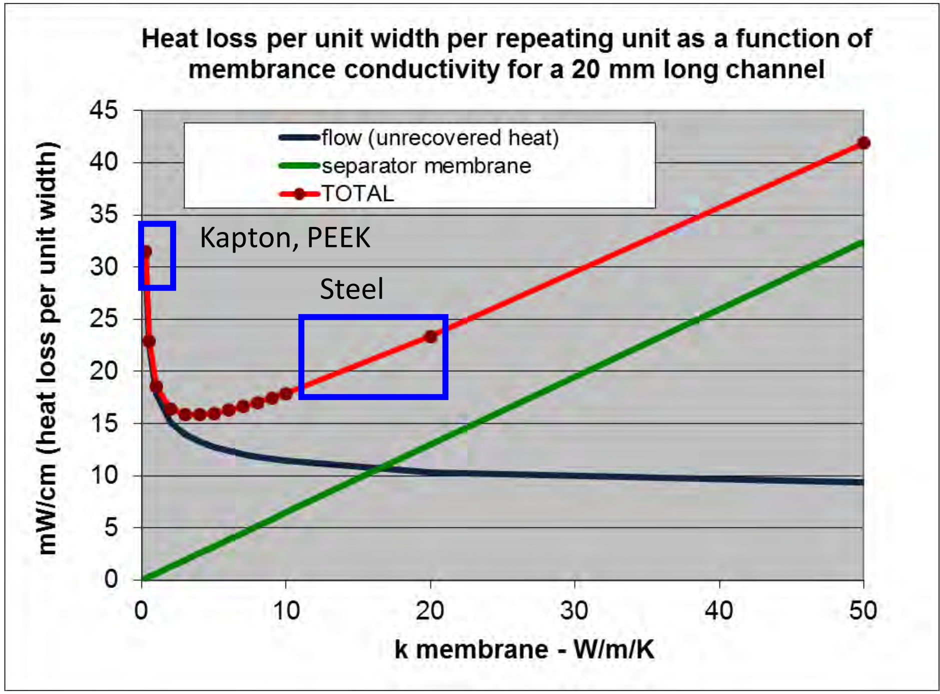
Heat loss tradeoffs (unrecovered heat in fluid and loss through membrane by axial conduction)

With Channel Length



With Membrane Thermal Conductivity



- ***Longer is better***
- ***but with diminishing returns***

- ***there is an optimal membrane thermal conductivity for any given length.***

*For case where liquid is water , channels are 40 um deep separated by 10 um thick membranes, average flow speed is 33.8 mm/s

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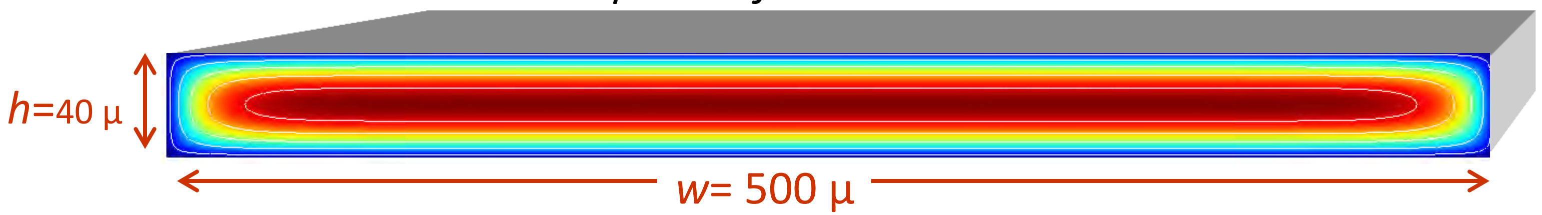
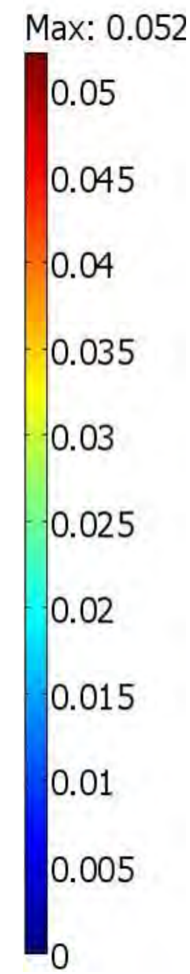
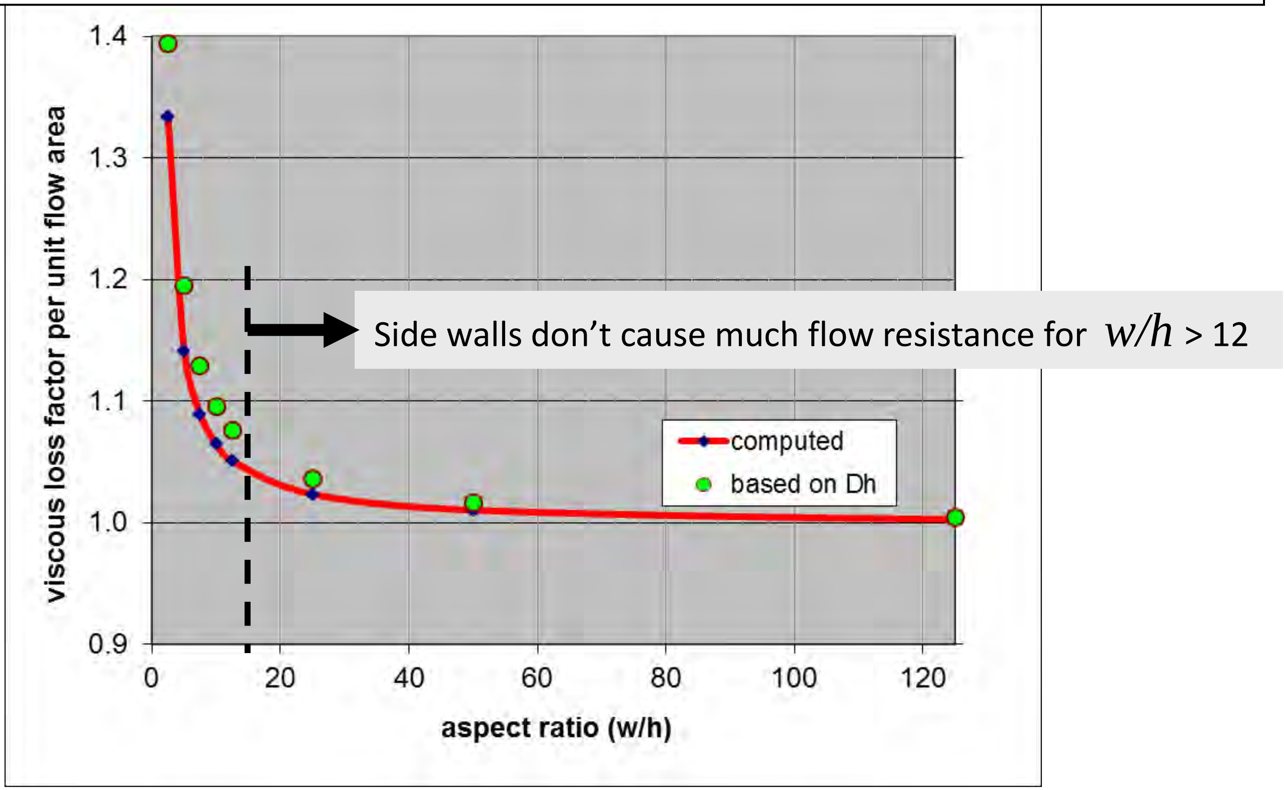
Pressure drop with fully developed velocity profile in rectangular duct

Flow below is into the plane of view





Effect of aspect ratio on viscous pressure loss per unit flow per unit area



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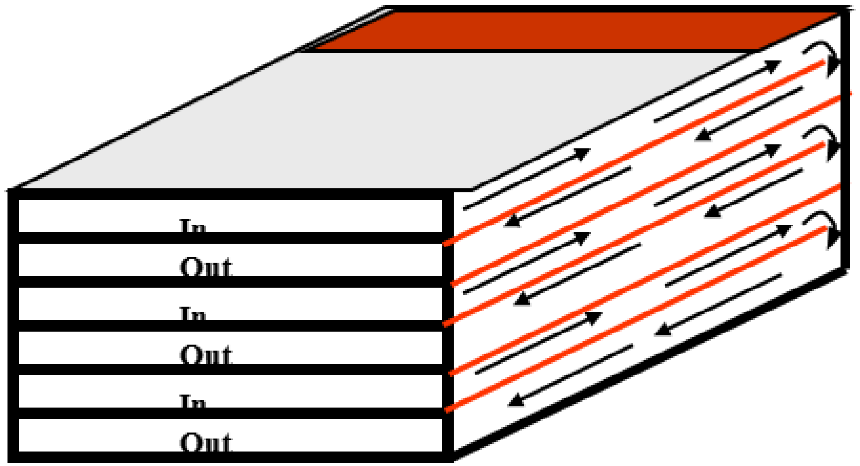
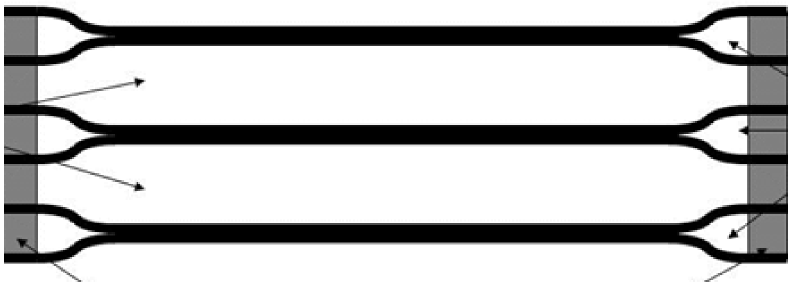
Membrane collapse problem

Alternating channels of high-low pressure (order of 2-3 bars difference)





Channels would collapse without support

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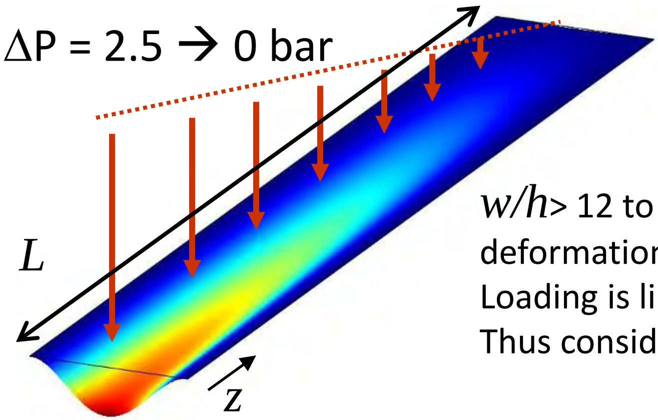
Structural analysis of membrane deflection



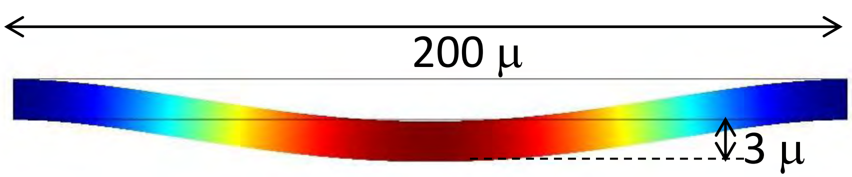
$w/h > 12$ to avoid additional pressure drop penalty but results in too much deformation (with h=40 um)

Loading is linear in flow direction and deflection ~ load

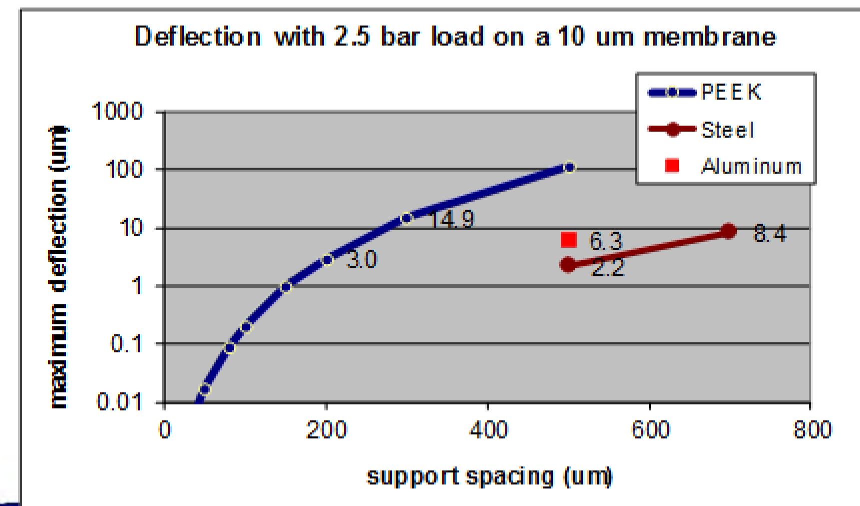
Thus consider a sparse array of supports linearly spaced in z- direction

$$w_s(z) = w_{s,\min} \Delta P \frac{z}{L}$$

Model the highest stress segment as 2-D plane strain problem



10 um thick PEEK membrane under 2.5 bar loading



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Limiting the membrane deformation

Because pressure loading decreases in axial direction, supports can be made more sparse in lower pressure regions

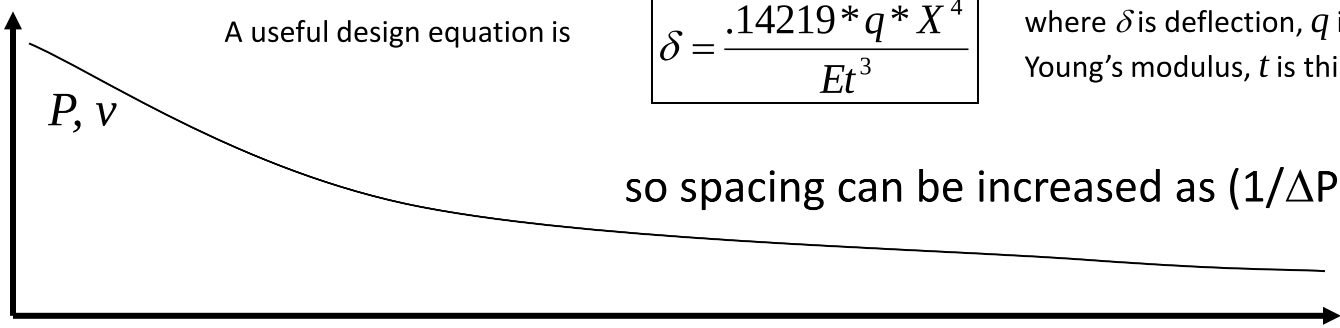
- Other complications:

- But uneven spacing of supports will cause pressure drop profile to be nonlinear
- Interstitial velocity will vary axially – hold time calculation may not be straightforward

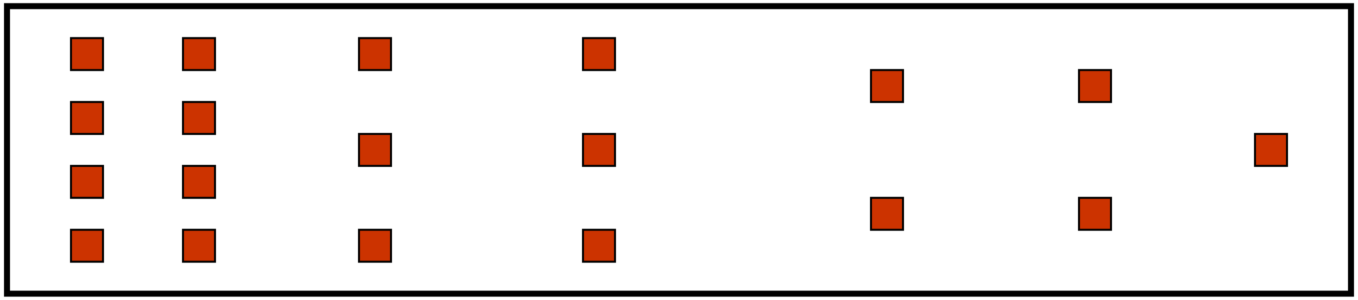
A useful design equation is

$$\delta = \frac{.14219 * q * X^4}{Et^3}$$

where δ is deflection, q is load, X is spacing, E is Young's modulus, t is thickness



so spacing can be increased as $(1/\Delta P)^{0.25}$



Entry/exit end *U-turn end*

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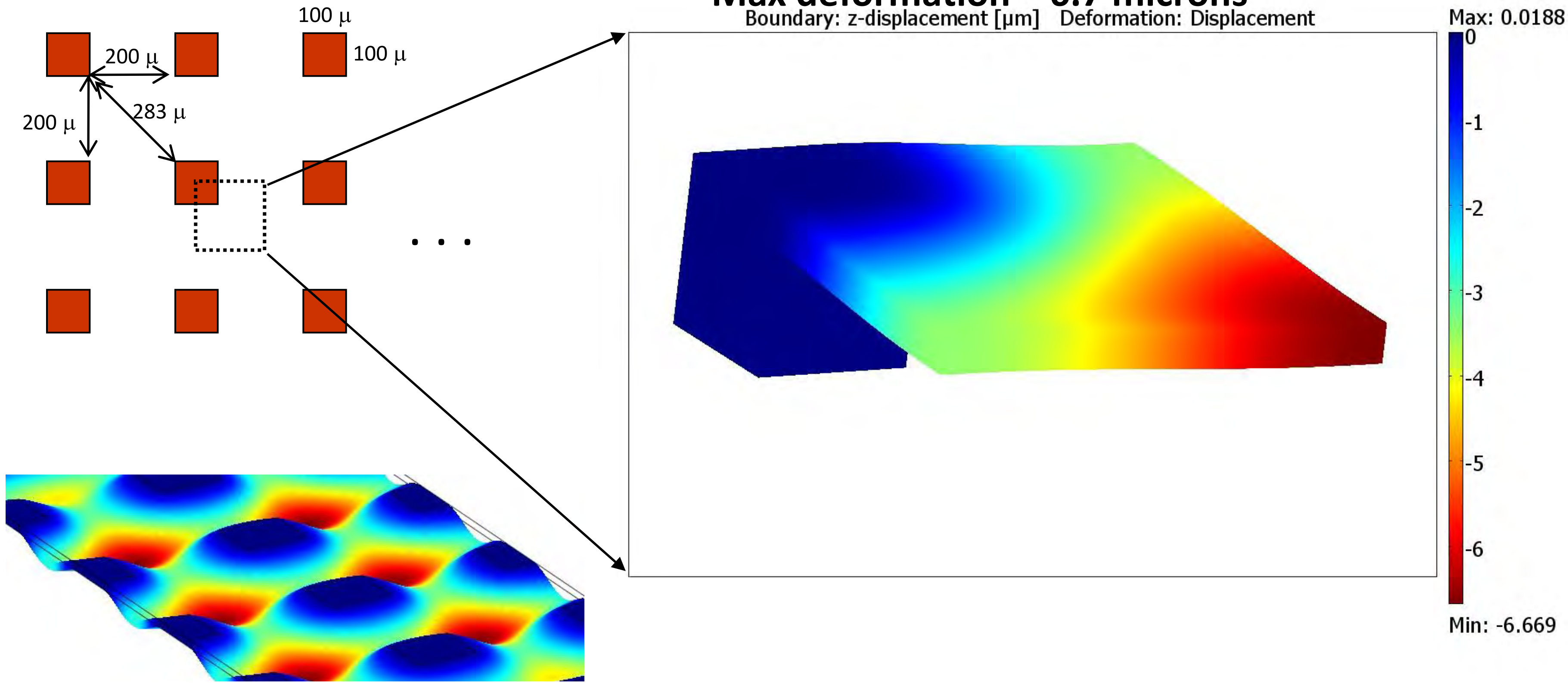
3D deformation analysis – linear Cartesian grid

Shown below is a portion of the 12.5 um thick PEEK (3 GPa) membrane under 2.5 bar load supported by a Cartesian array of 100um by 100um square posts with 200 um X-Y gap between.

CLOSEUP OF A REPEATING UNIT

Max deformation ~ 6.7 microns



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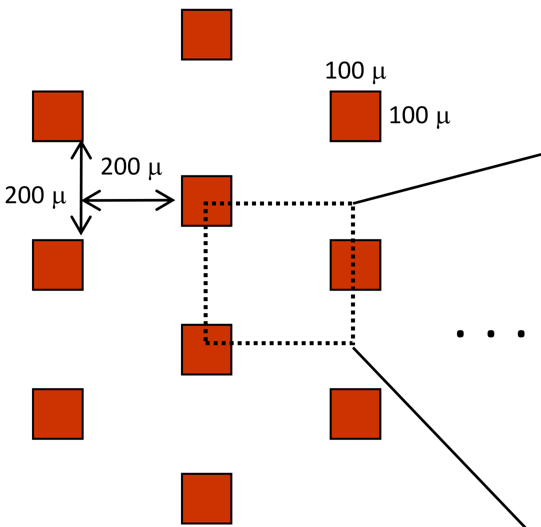
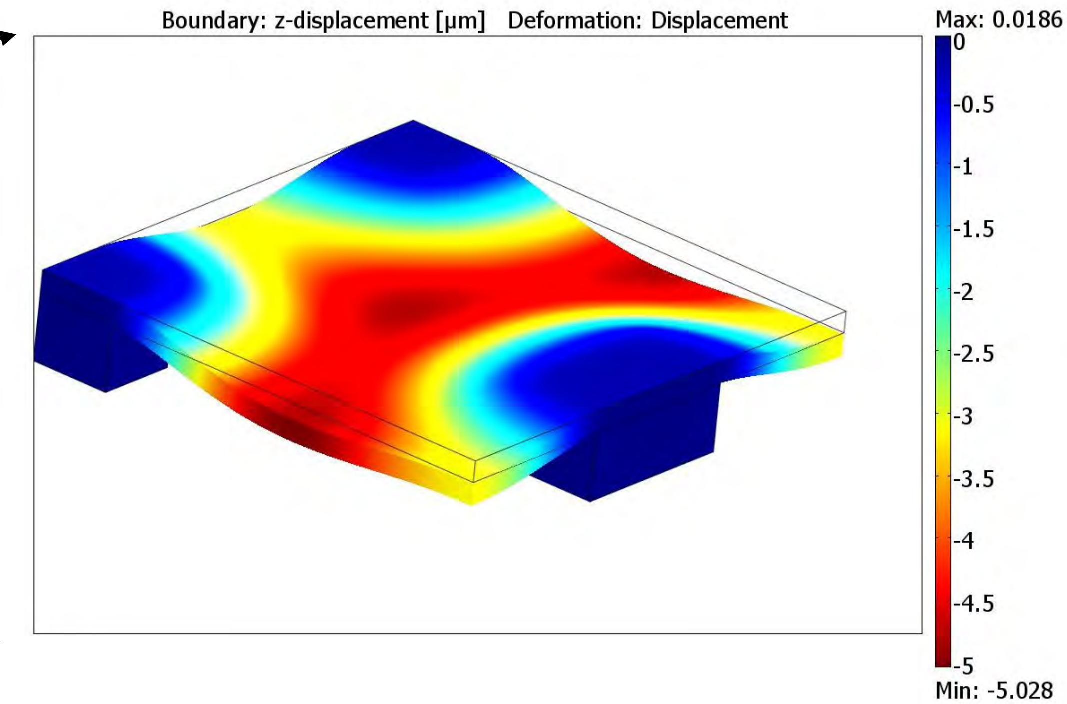
3D deformation analysis – staggered Cartesian grid

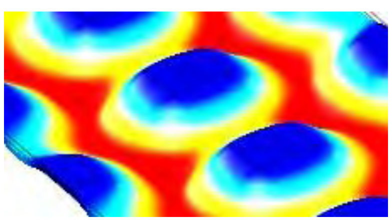
Shown below is a portion of the 12.5 um thick PEEK (3 GPa) membrane under 2.5 bar load supported by a staggered Cartesian array of 100um by 100um square posts with 200 um X-Y gap between.



CLOSEUP OF A REPEATING UNIT

Max deformation ~ 5 microns





Staggering the supports decreases deformation by 35%

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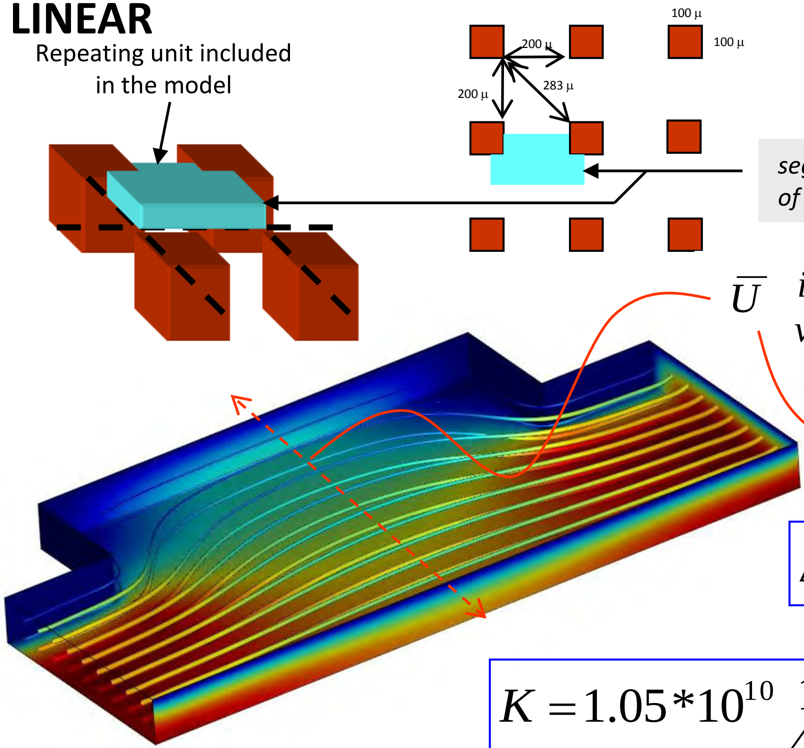
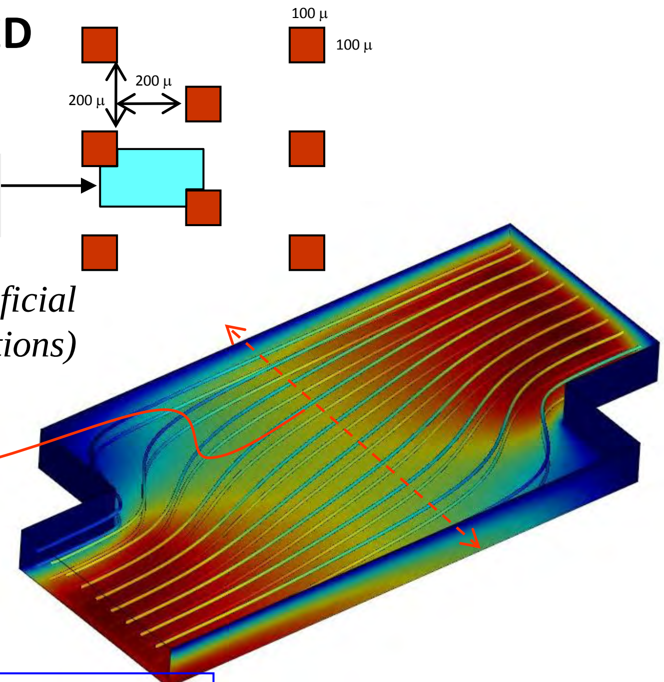
Pressure drop consequences of support posts: Linear vs. staggered

LINEAR

Repeating unit included in the model



STAGGERED



segment modeled is 1/50,000dths of one loop

$\overline{U}$ *is the bulk average superficial velocity (with no obstructions)*

$$\Delta P = K \mu L \overline{U}$$

$$K = 1.05 * 10^{10} \ {}^{1}\!/_{m^2}$$

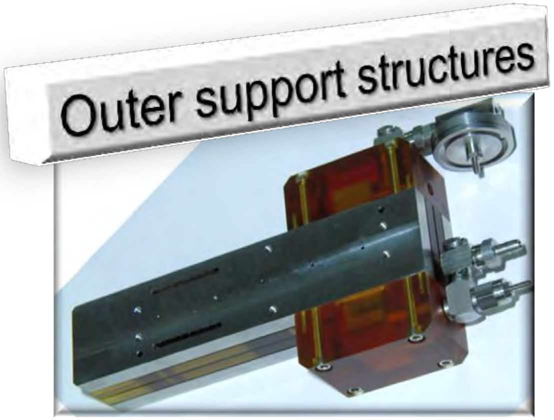
$$K = 1.07 * 10^{10} \ {}^{1}\!/_{m^2}$$

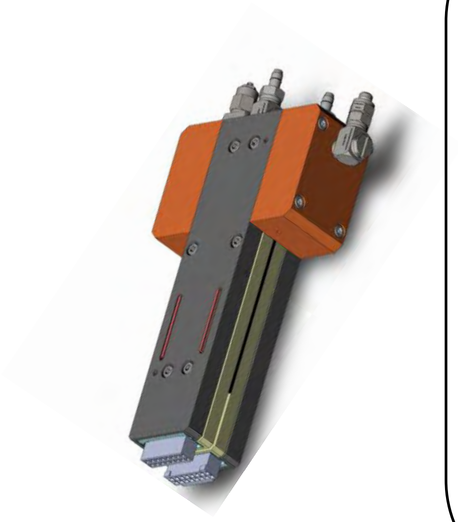
$$K = 0.75 * 10^{10} \ {}^{1}\!/_{m^2}$$

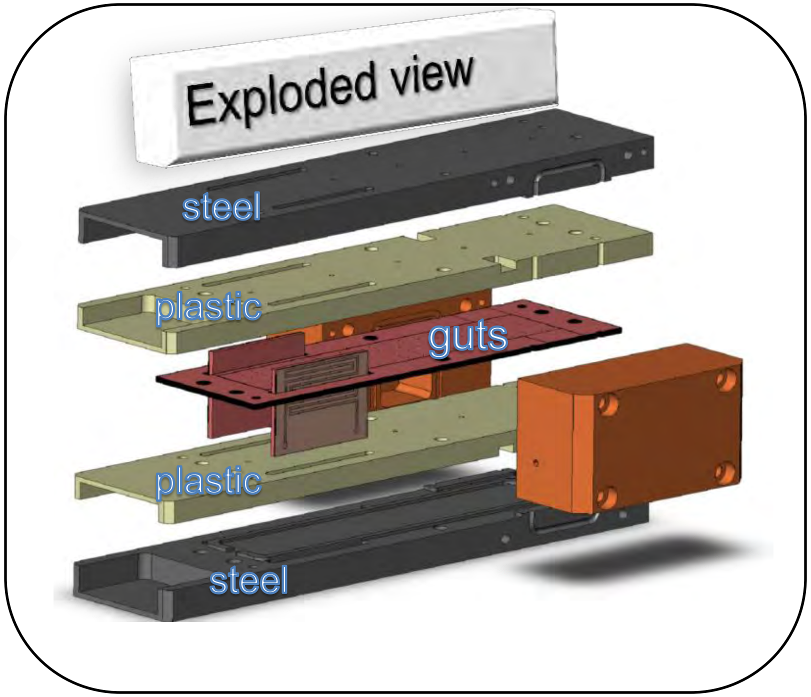
for wide open channels (no posts)

- *Support pillars add 40% flow resistance compared to wide open channels → compensate by adding width*
- *No significant fluidic difference between linear vs. staggered support arrays*

Fully integrated device







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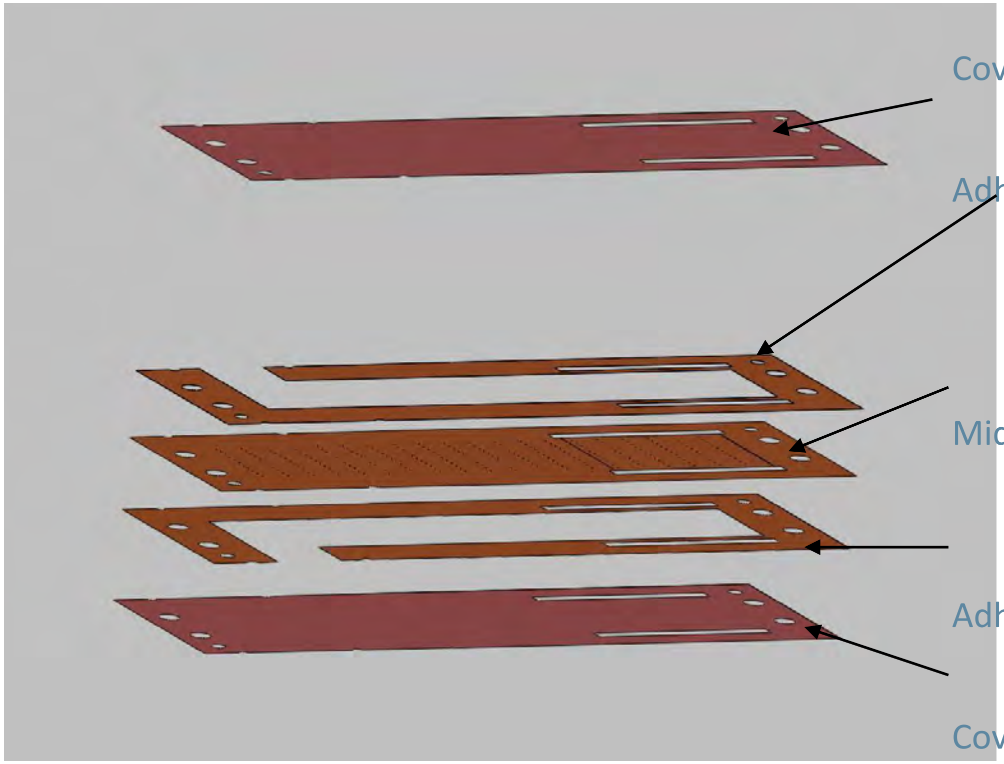
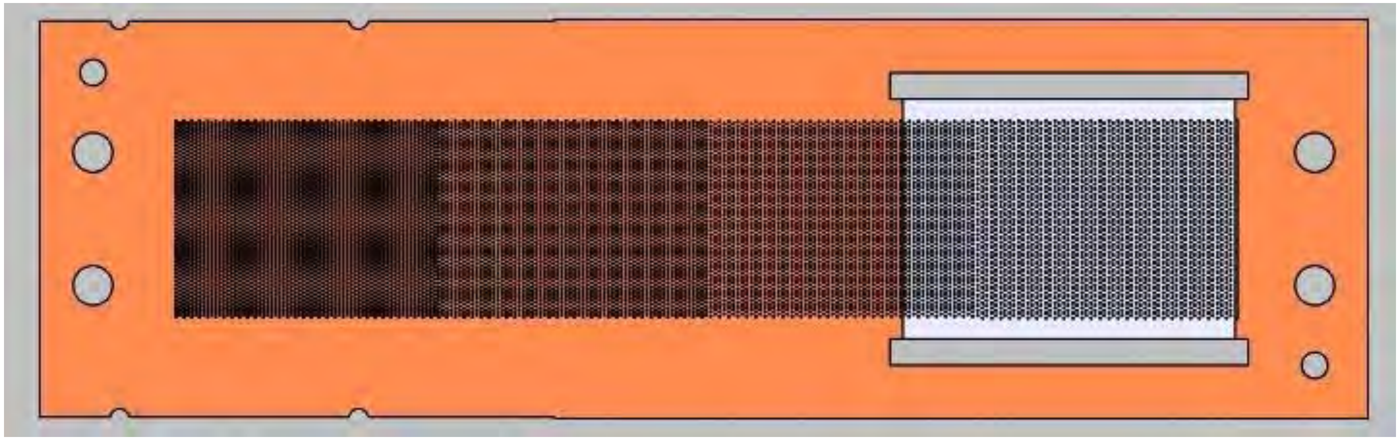
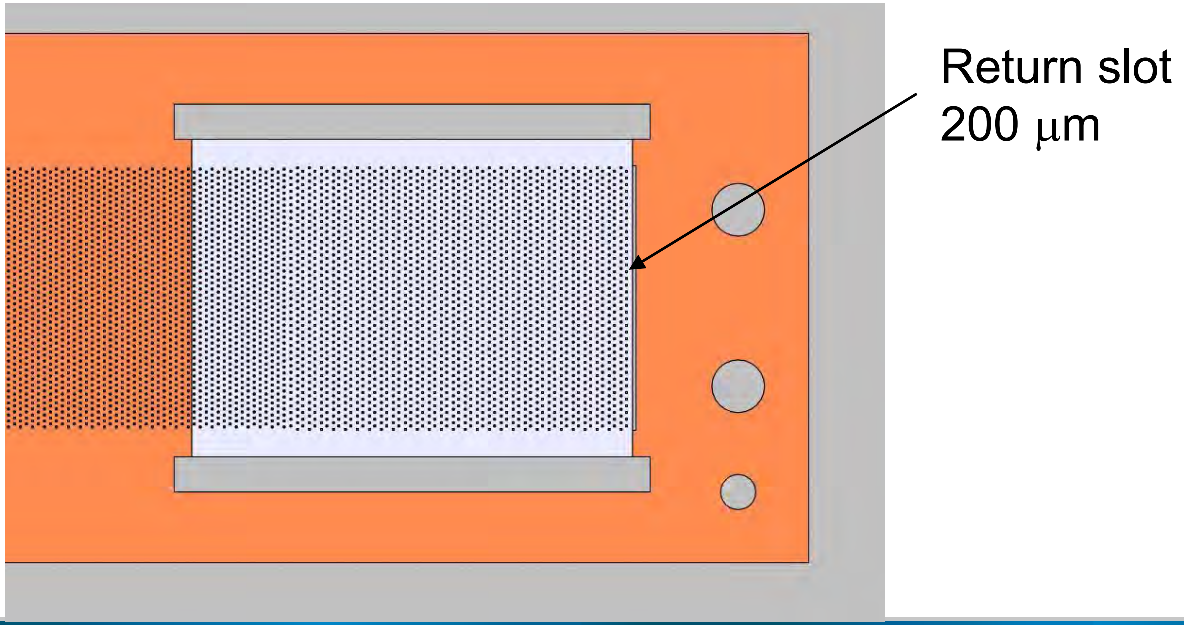
Exploded view of a pair unit



Mid Layer Construction





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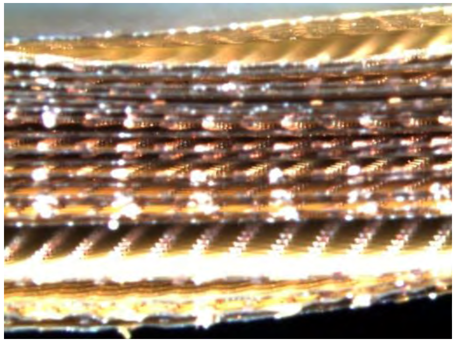
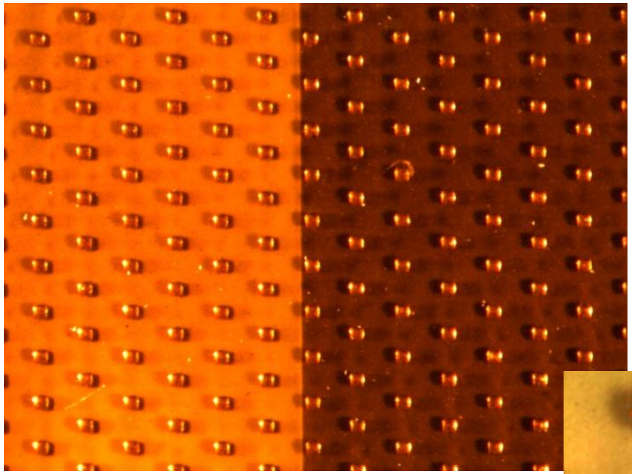
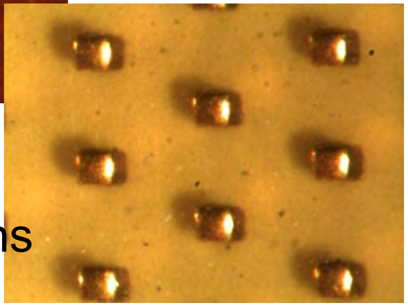
Photographs showing support posts



Arrays of support columns

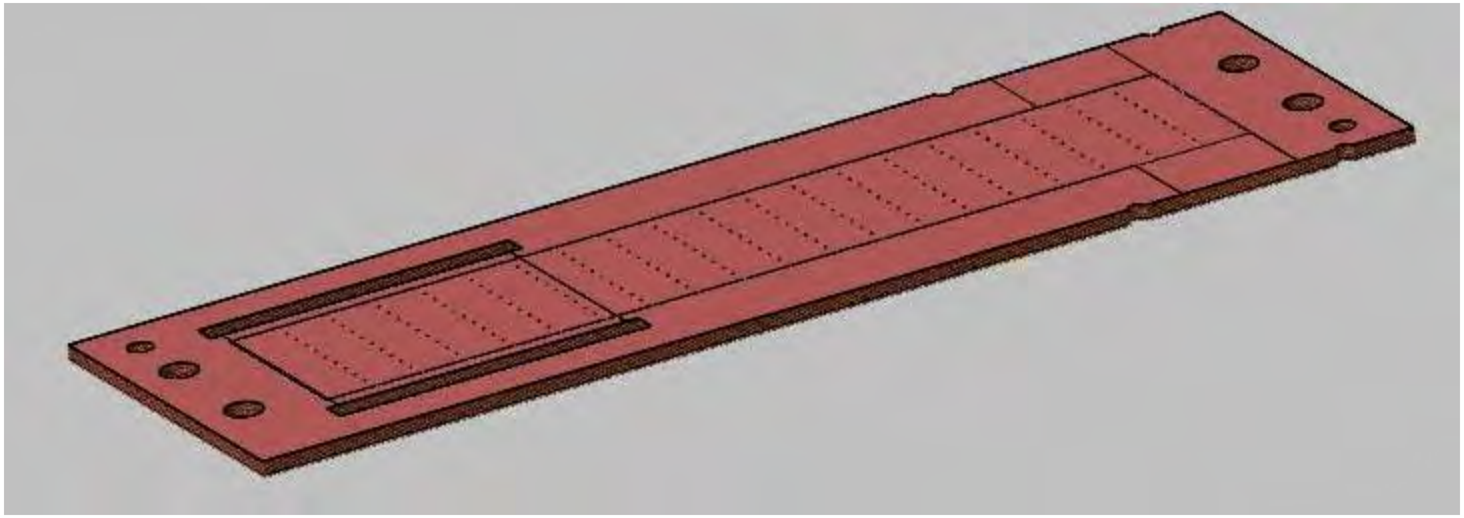




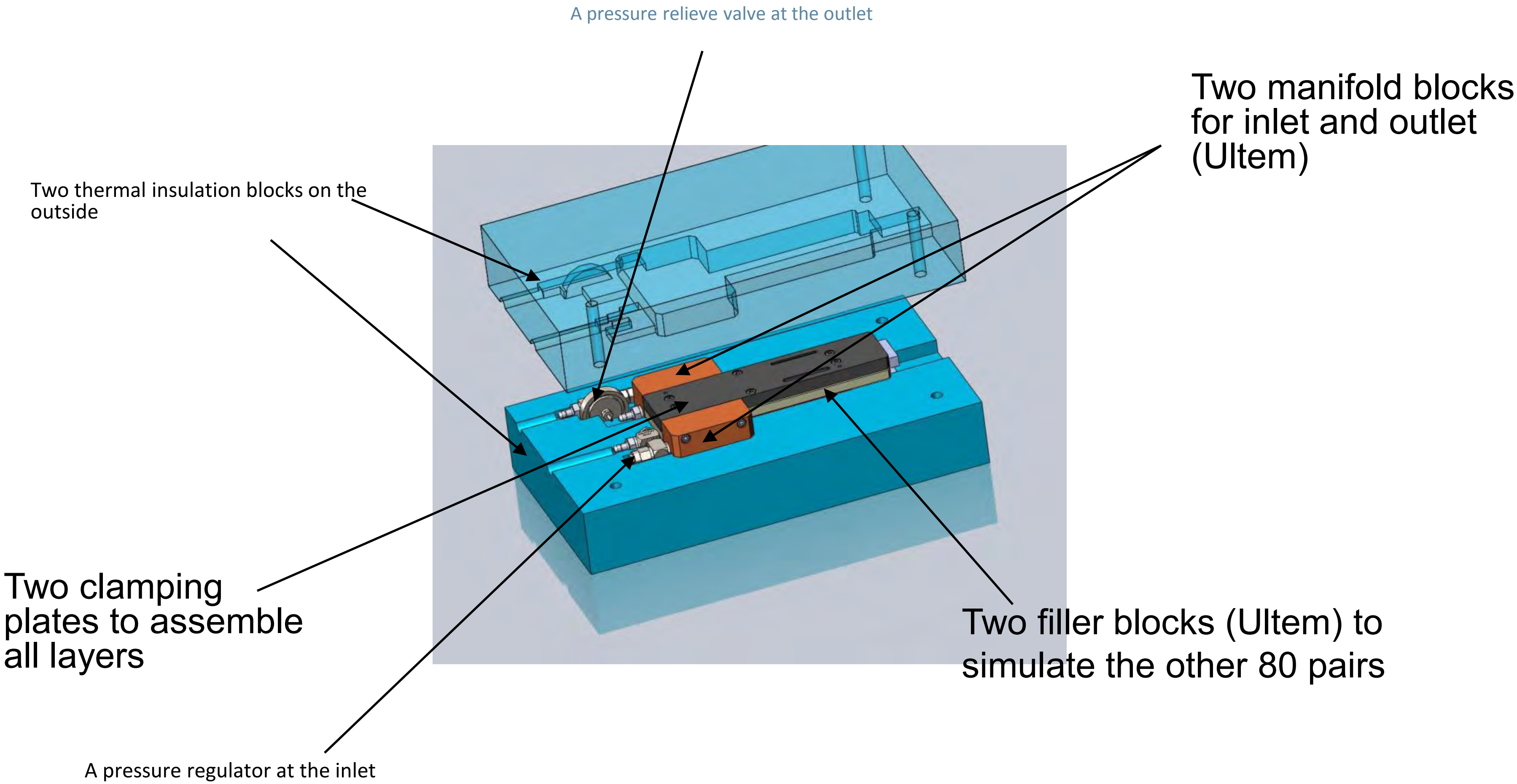
Staggered support columns

Ten Pair Construction

All ten pairs are assembled by heat seal under pressure .



Device final assembly



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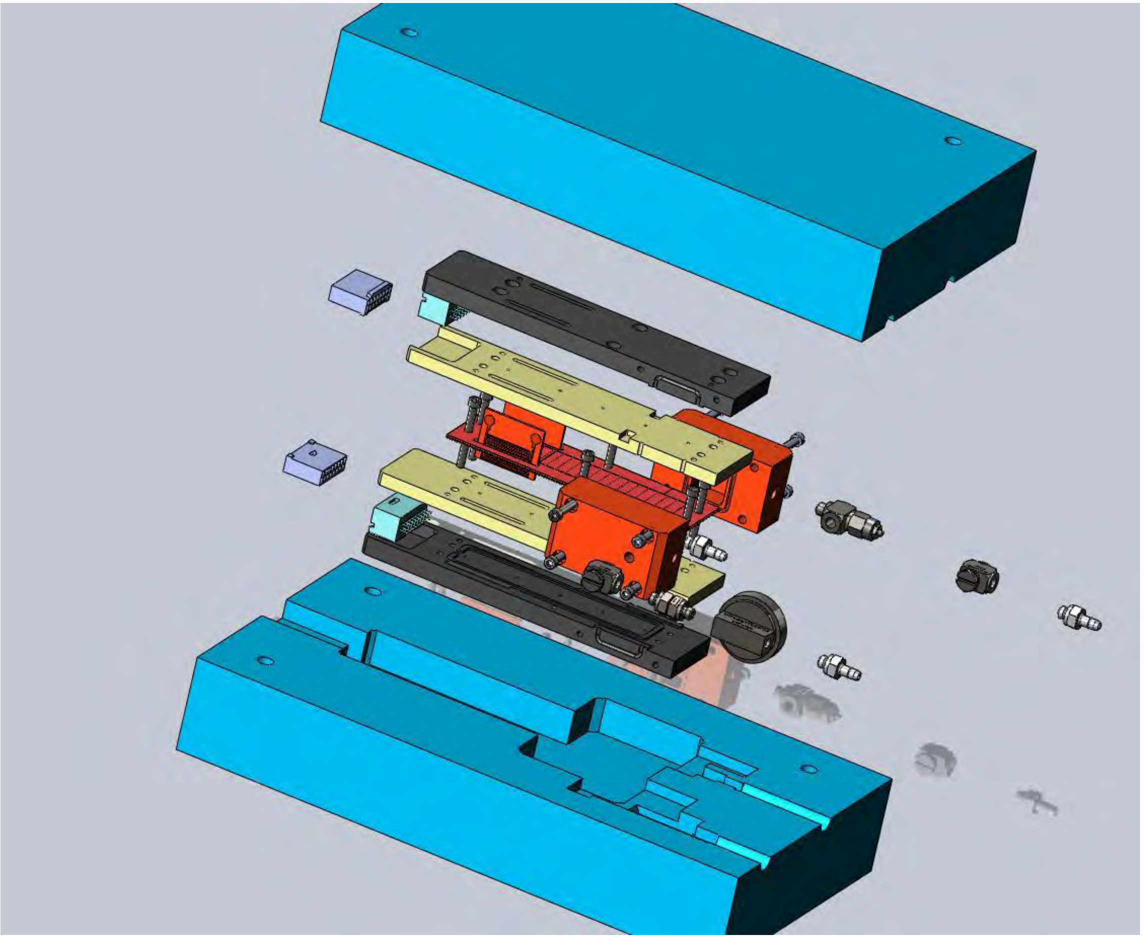
Device final assembly – exploded view



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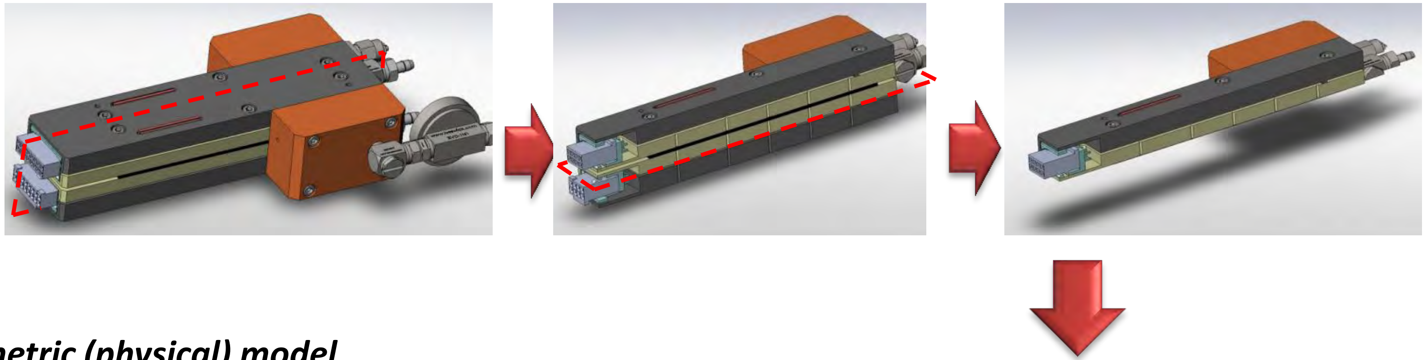
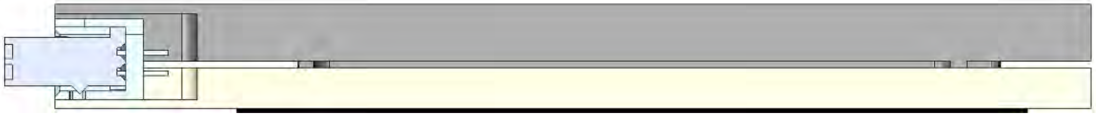
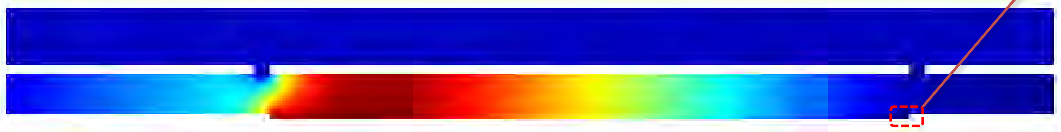
Thermal modeling of integrated device

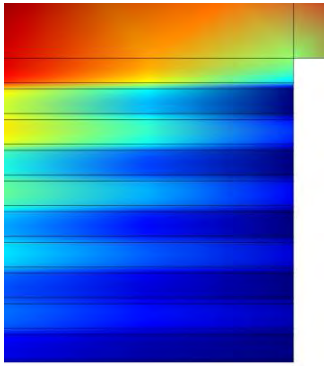


Geometric (physical) model



Thermo-fluidic (physics) model





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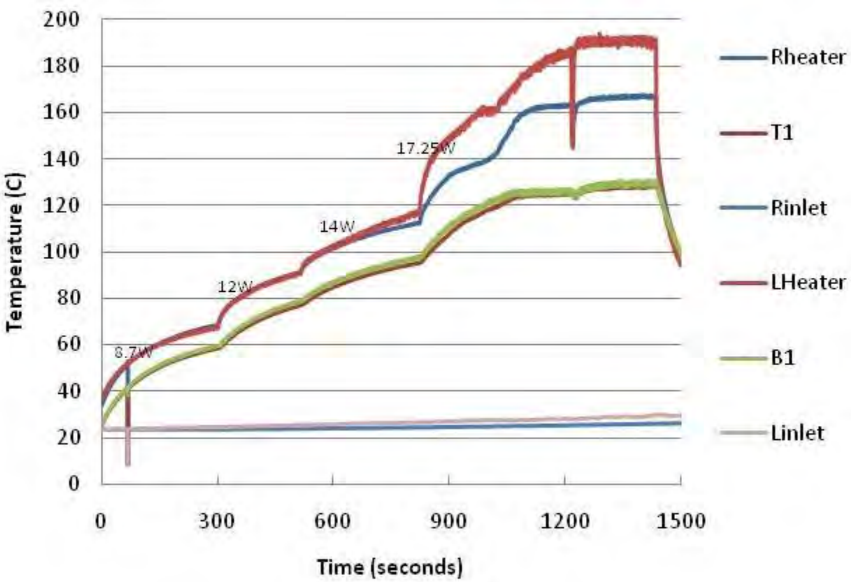
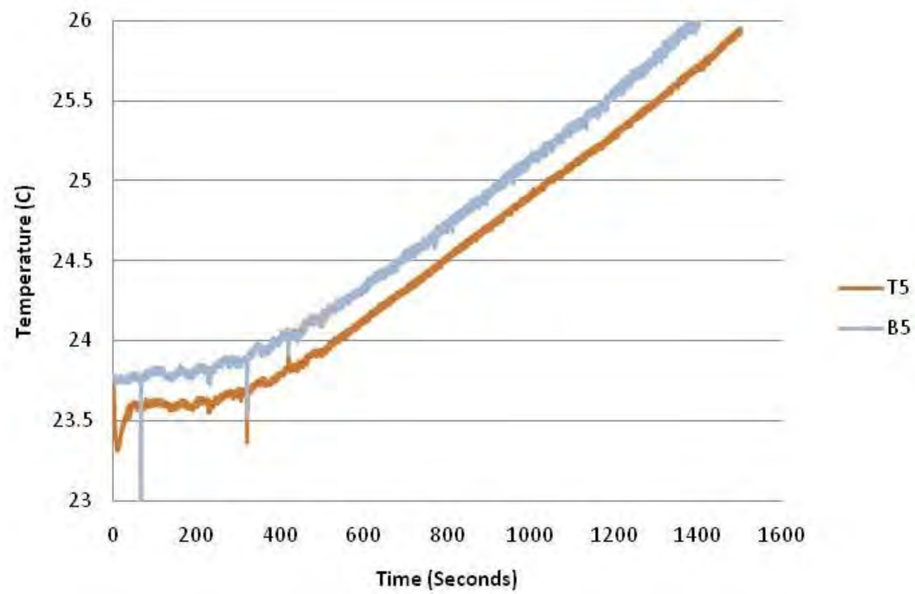
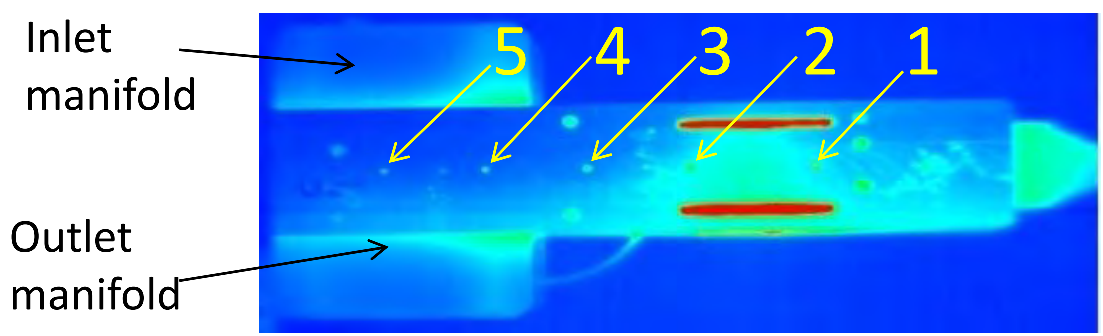
Temperature distribution in the device







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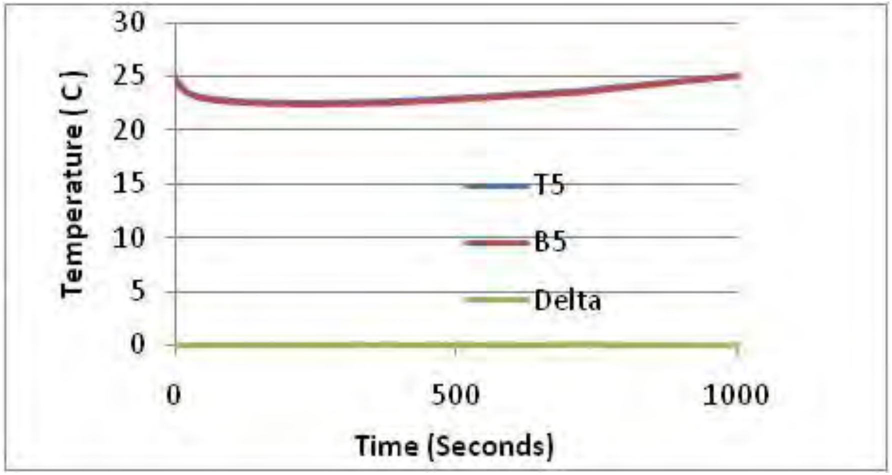
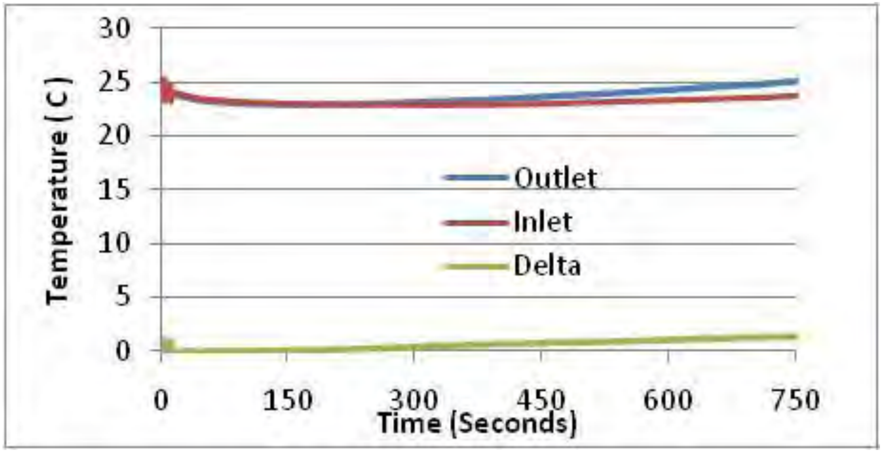
Results on efficiency

- Device was able to cycle the water temperature from ~ 20 C → 120 C → 20 C within a few seconds with excellent heat recapture. (Water temperature ΔT between the inflow and outflow at location 5 was less than 0.5 C)
- Water temperature ΔT between the inlet and outlet manifolds increased from 0 to 1.5 C.
  - The manifolds and the metal blocks at the inlet/outlet might have contributed to the temperature differences.
- As expected, the electrical power supplied was larger than explained by unrecovered amount during regeneration based on other inefficiencies that were not optimized
  - The package assembly also heated up and conducted heat axially.
  - Heat loss to the ambient environment added further inefficiency to the system.





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Closing remarks

- COMSOL used effectively in developing the microchannel regenerative heat exchanger concept on thermal, fluidic, and structural fronts
- Physical prototype confirmed high regenerative efficiency of the basic concept. Additional inefficiencies (imperfect thermal contact from heaters, package design etc.) were not the primary focus of this project.

Questions?

BACKUP SLIDES

Basic causal relations and tradeoffs

low power requirement

long flow time compared to thermal diffusion times

efficient heat recovery

minimize heat transfer resistance in membrane

thin membrane

countermeasures against membrane collapse

maximize heat exchange surface

long channels

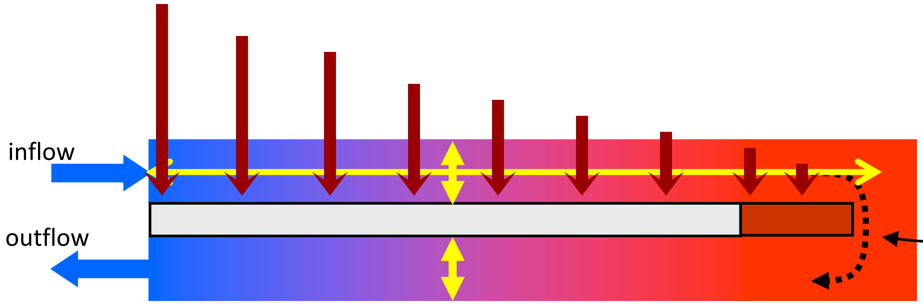
minimize heat transfer resistance in liquid

shallow channels

little flow per channel

multiple channels

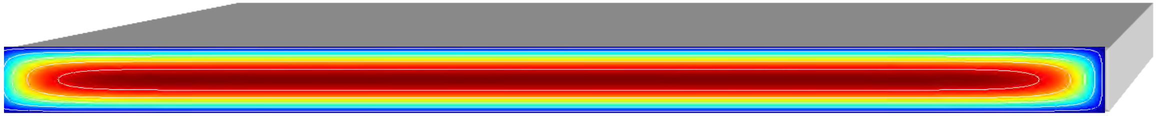
large pressure drop



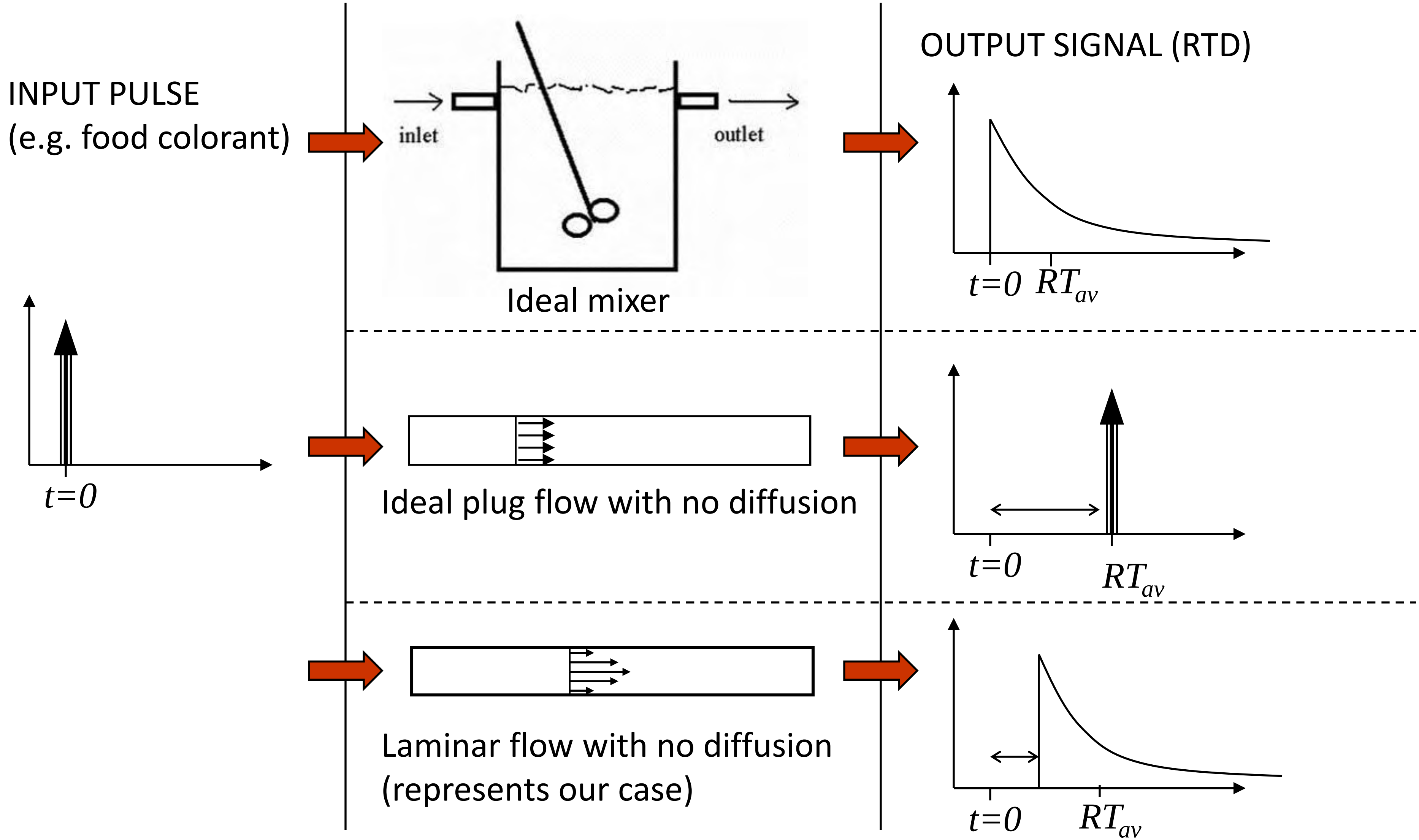
region at 135 ^{0}C. Must maintain high pressure to prevent boiling

Fluid kinematics analysis :

Residence Time Distribution – *RTD*



What is Residence Time Distribution (RTD)?



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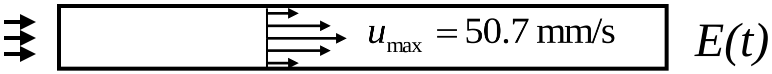
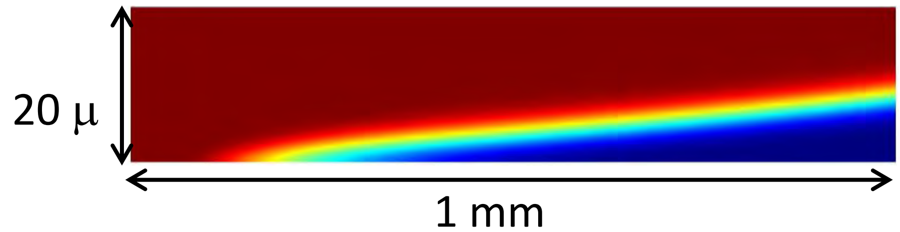
Computed RTD- 1 mm downstream, Pe = 10000*

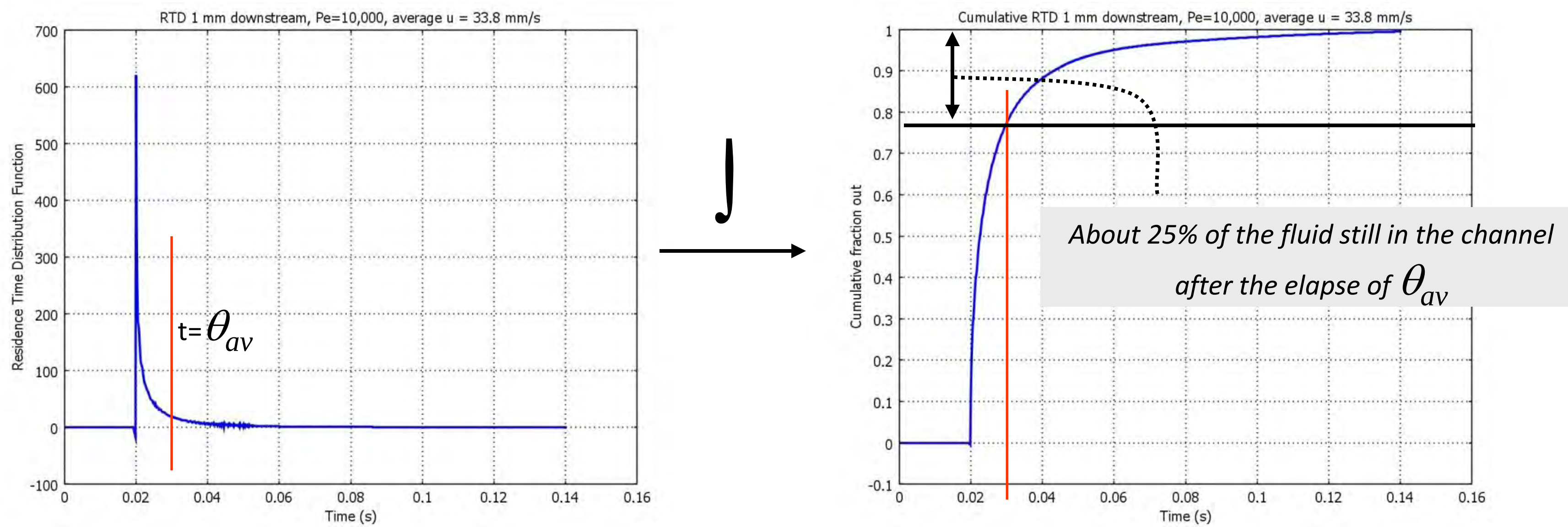


$\bar{u} = 33.8$ mm/s

Thus, minimum RT, θ_{min} = 1/50.7 = 0.02 sec
Average RT, θ_{av} = 1/33.8 = 0.03 sec

Concentration profile of the tracer after stepwise introduction and θ_{av} elapsed





** Estimated Pe in the device is 35,000 , but results are insensitive to Pe for Pe>10,000*

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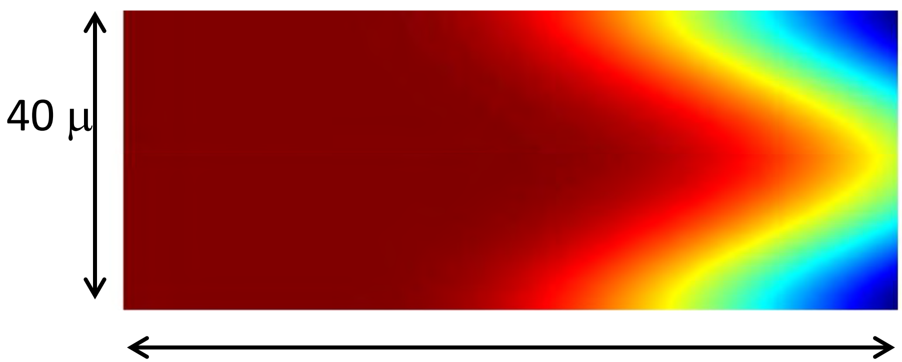
Computed RTD at two Peclet numbers

Concentration profile of the tracer after stepwise introduction of a “tracer” and average residence time θ_{av} has elapsed

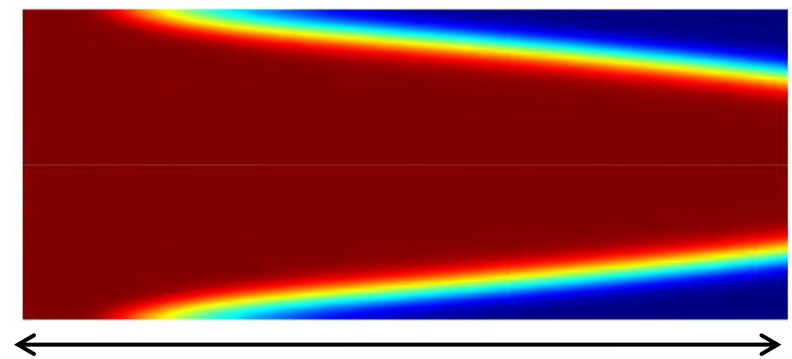
$Pe = 100$



1 mm

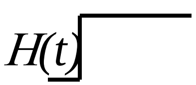
significant diffusive dispersion

$Pe = 10000$



1 mm

no diffusive dispersion



$$Pe = \frac{UL_c}{D}$$