Tritium Extraction using Compact Heat Exchangers

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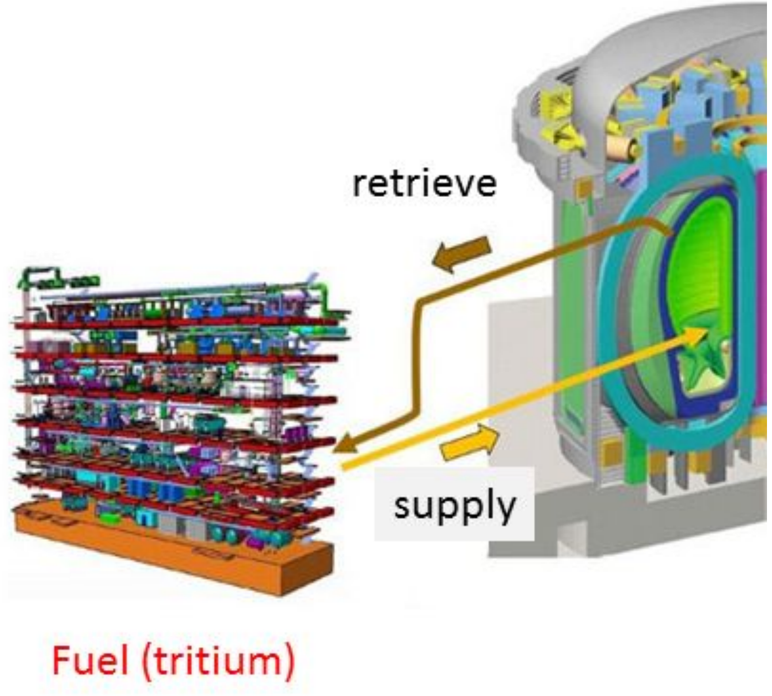
The HEAT Lab
High-temperature Energy-system and Advanced Technology

Tritium Challenges in Fusion Energy

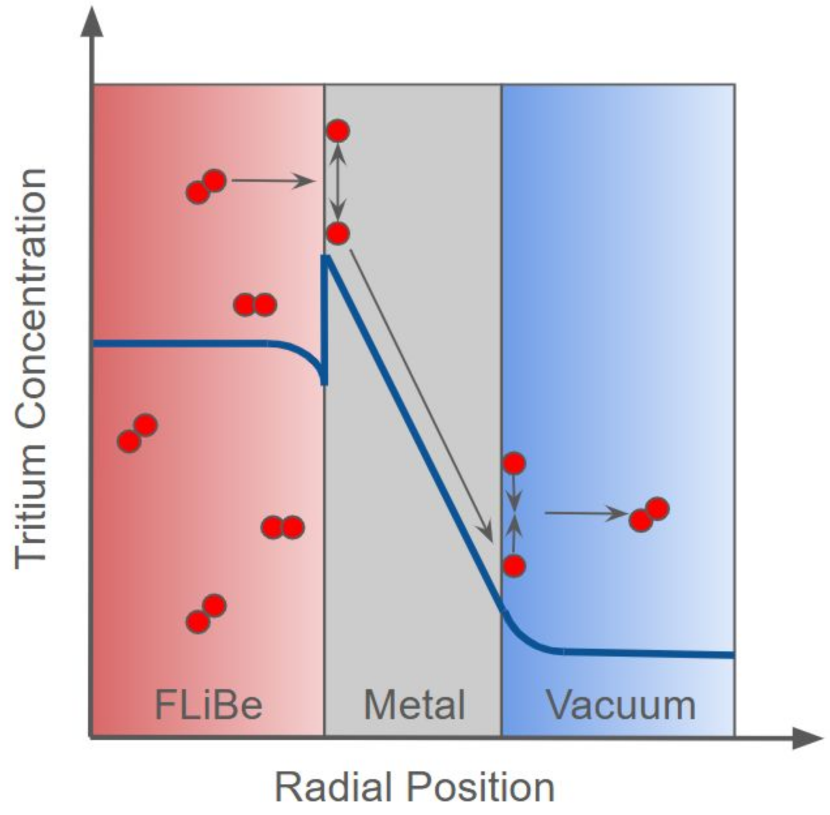
$$ {}^{6}_{3}\mathrm{Li} + n \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{3}_{1}\mathrm{H} $$

- Tritium is expensive to produce
- Breeding blankets
  - FLiBe molten salt absorbs neutrons and produces Tritium
- **How can we extract this tritium for future fueling cycles?**



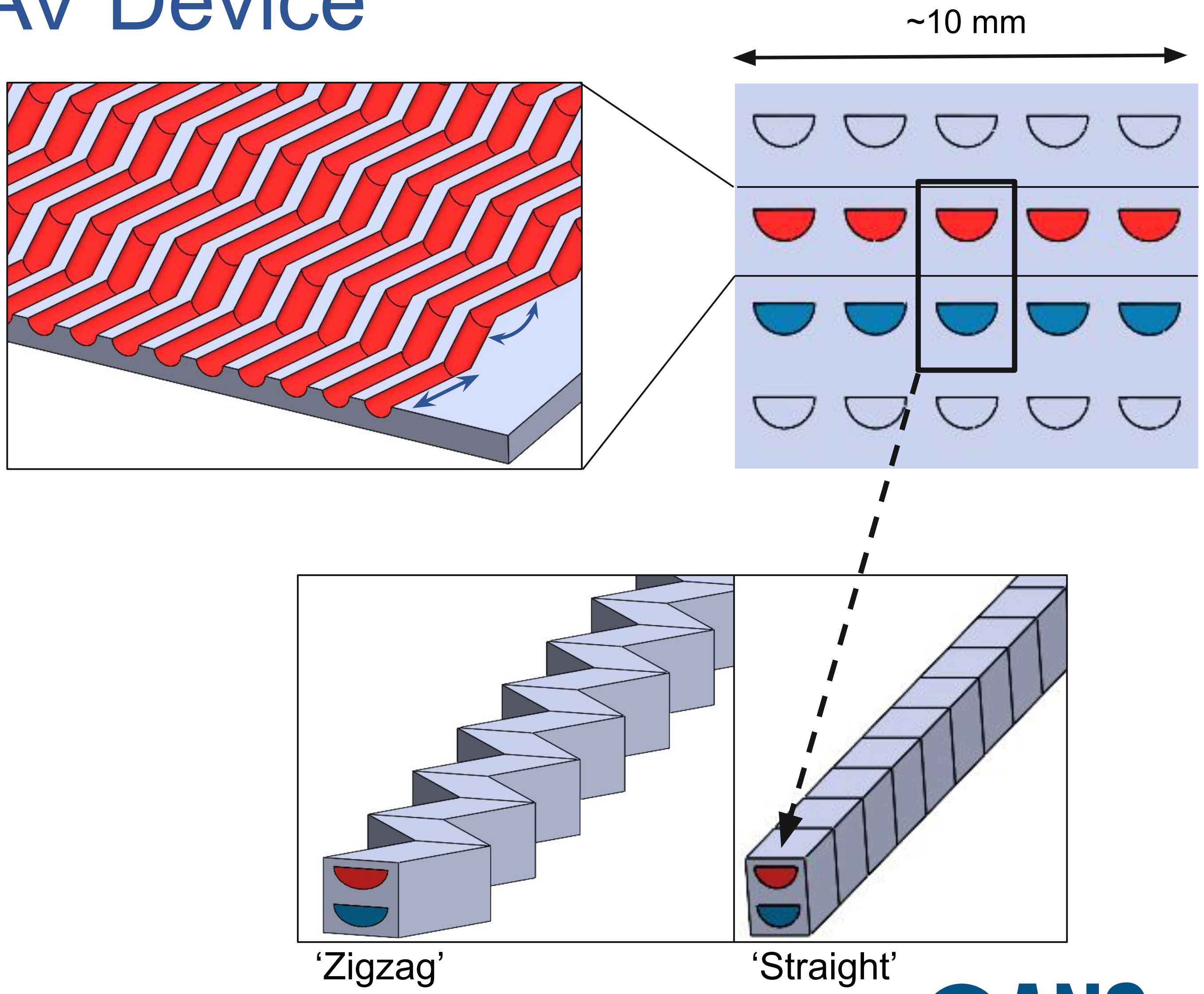
Existing Tritium Extraction Methods

- Electrolysis
- Gas-Liquid-Contactors
- Permeator-Against-Vacuum (PAV)



Heat Exchangers as a PAV Device

- Heat Exchangers
  - Heat and mass transfer similarity
- Printed Circuit Heat Exchangers (PCHEs)
  - Cheaper to manufacture
  - Large surface area density
  - Enhanced turbulent convective transport
  - Large amount of literature available!



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Simulation Assumptions & Models

- Steady-State
  - Temperature set to 900K
- Passive Scalars
  - Partial pressure and flux continuity enforced
- Vacuum Not Meshed
  - Zero tritium concentration
- > 50mm Total Channel Length
  - Ensure fully developed flow

STAR-CCM+

$$p_{Q_2} = Q_2/K_H = (Q/K_S)^2$$

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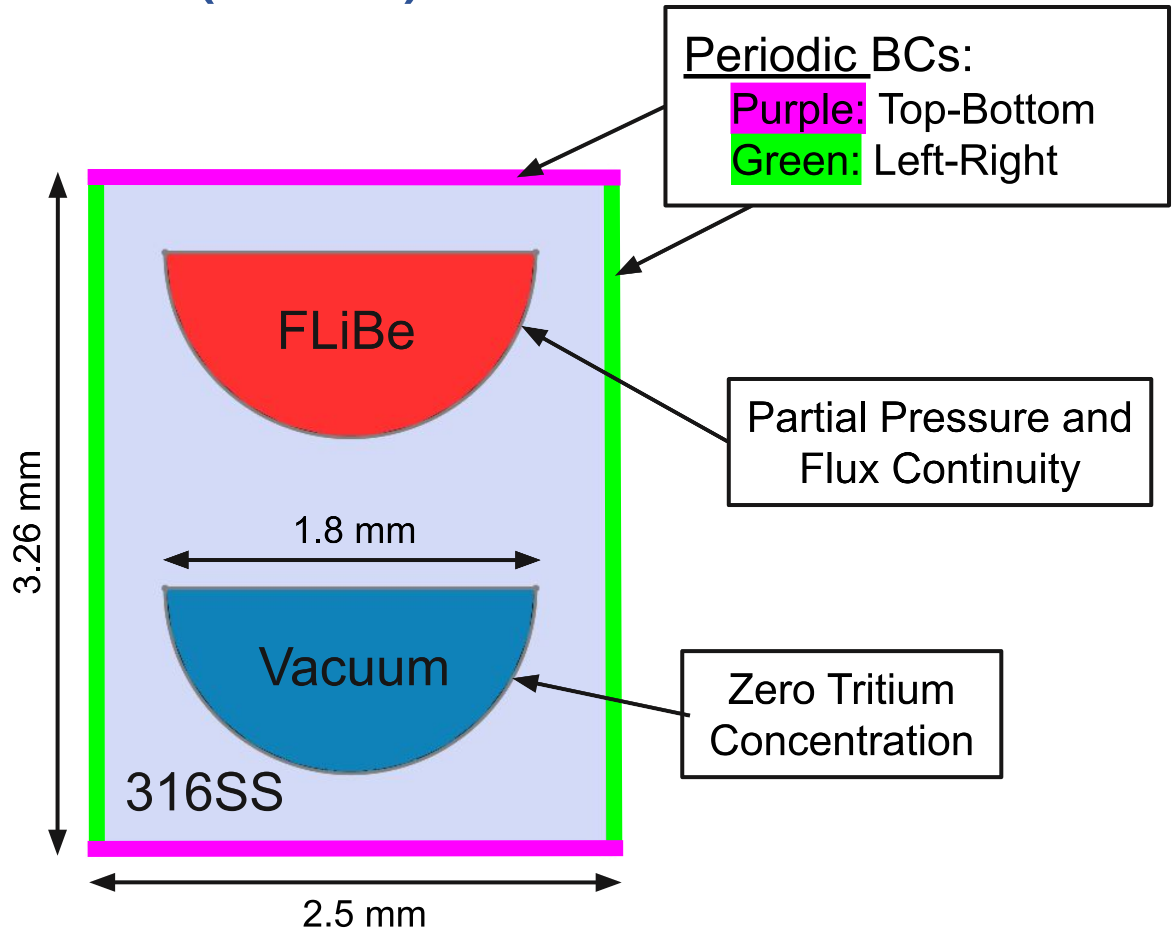
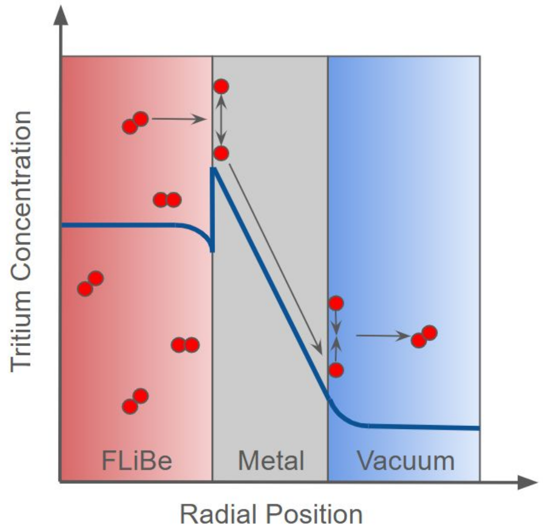
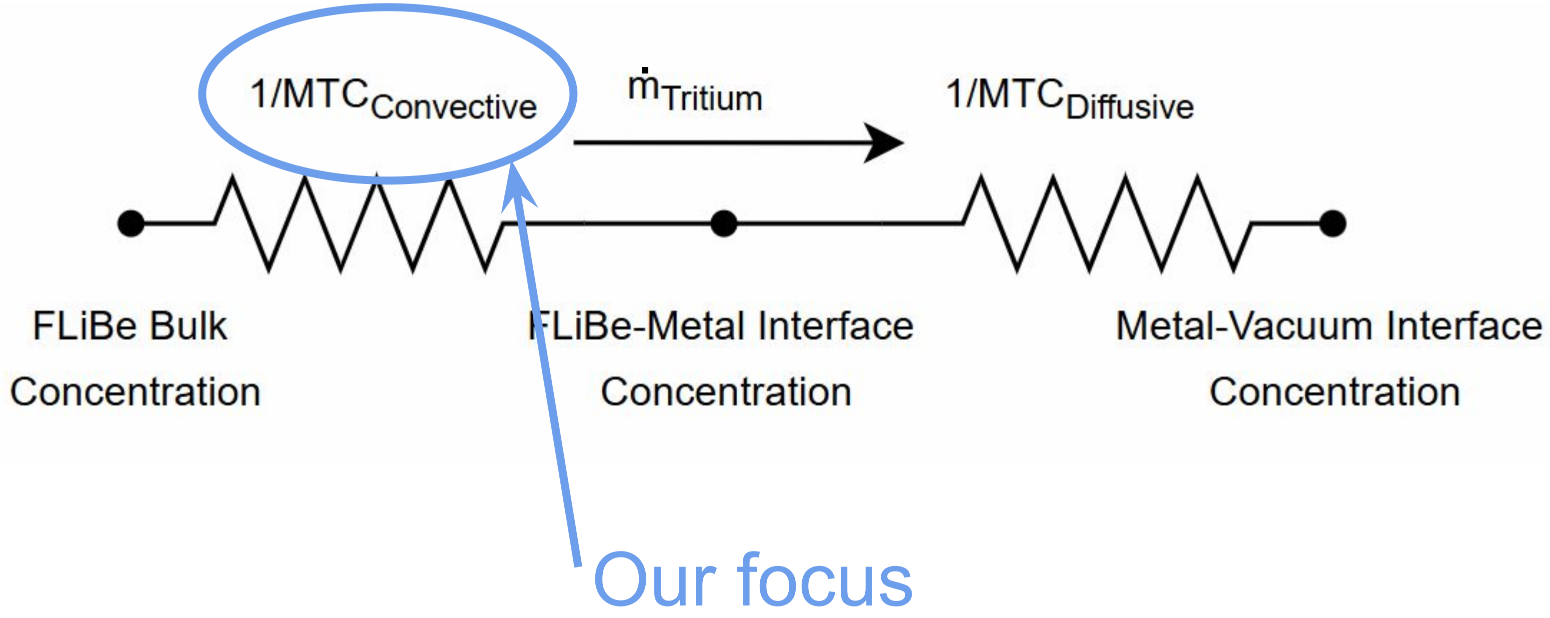
Materials & Boundary Conditions (BCs)

- 316 Stainless Steel (316SS)
  - Important constants and physics previously analyzed
- Boundary Conditions
  - Turbulent Inlet FLiBe Velocity: 15 m/s
    - Re > 4000
    - Pressure Gradients may be an issue
  - Laminar Inlet FLiBe Velocity: 1 m/s
    - Re << 2000
  - Inlet Source Concentration
    - 3.28E-9 mol/s for turbulent simulations
    - 2.19E-10 mol/s for laminar simulations

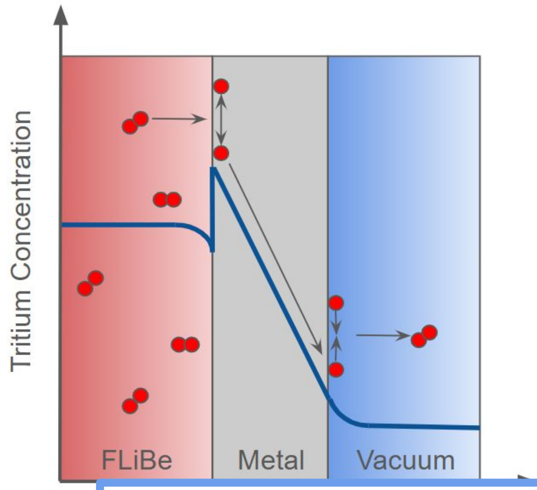


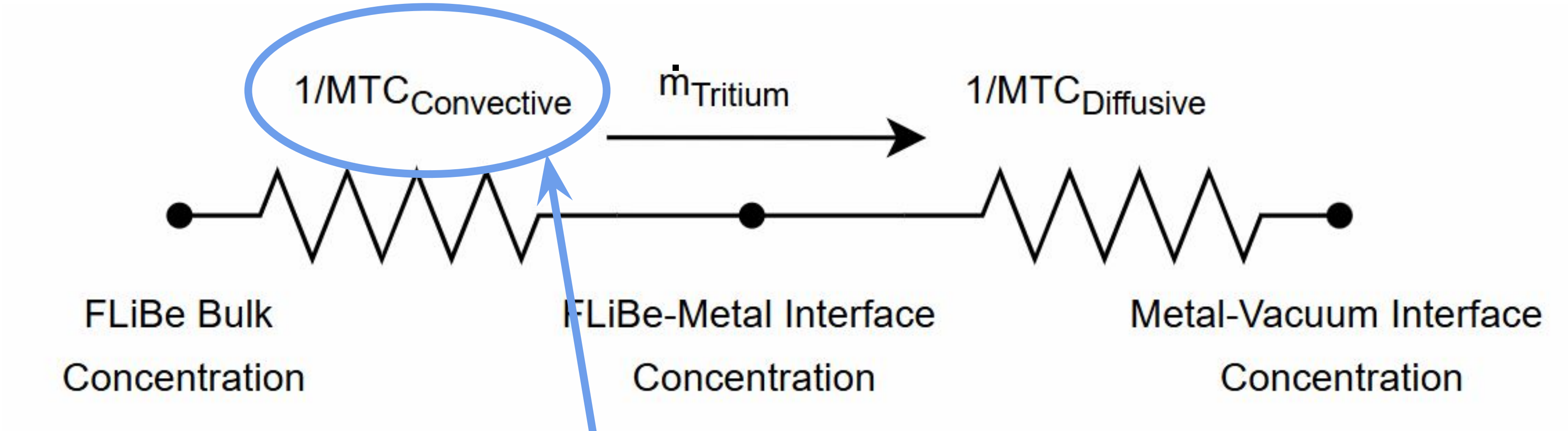
Mass Transfer Coefficient (MTC) Calculation





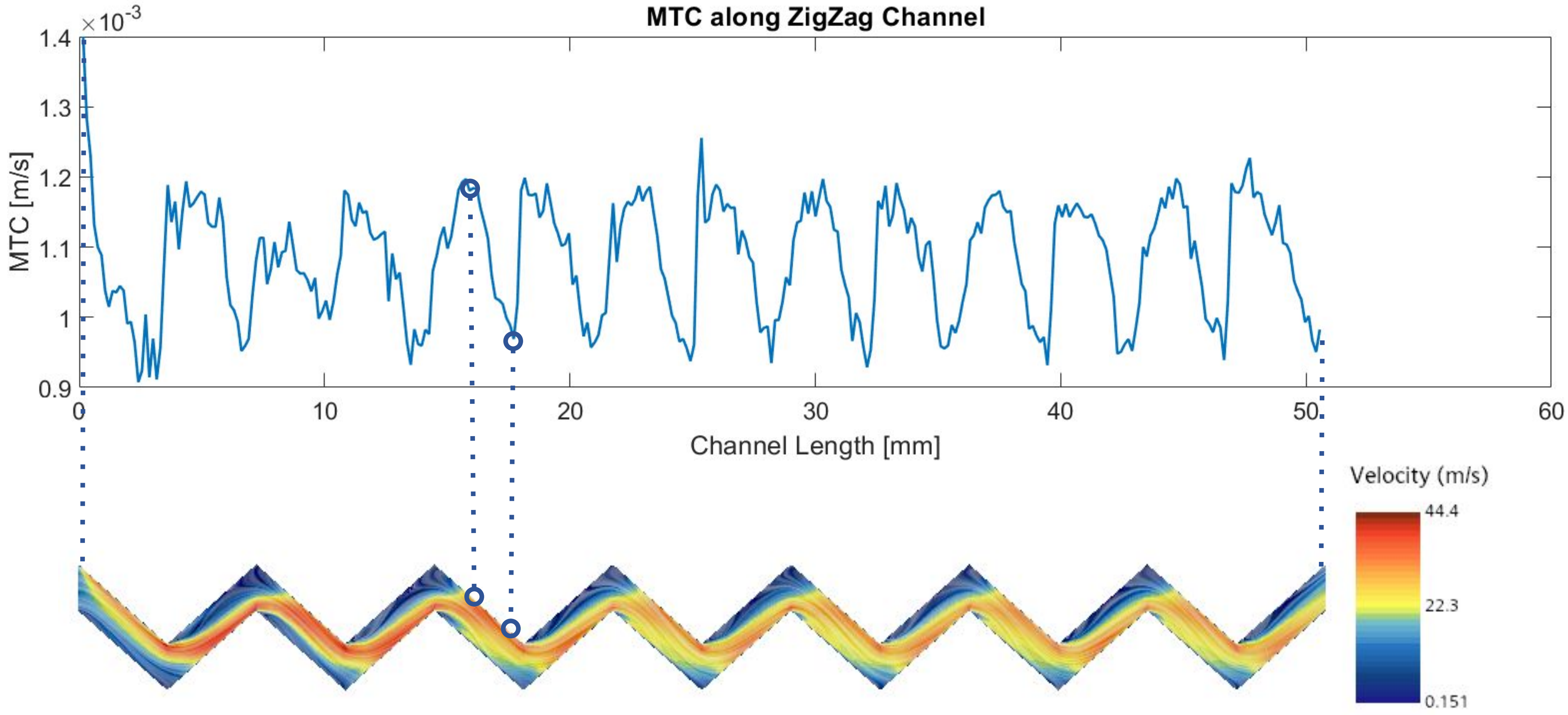
Mass Transfer Coefficient (MTC) Calculation



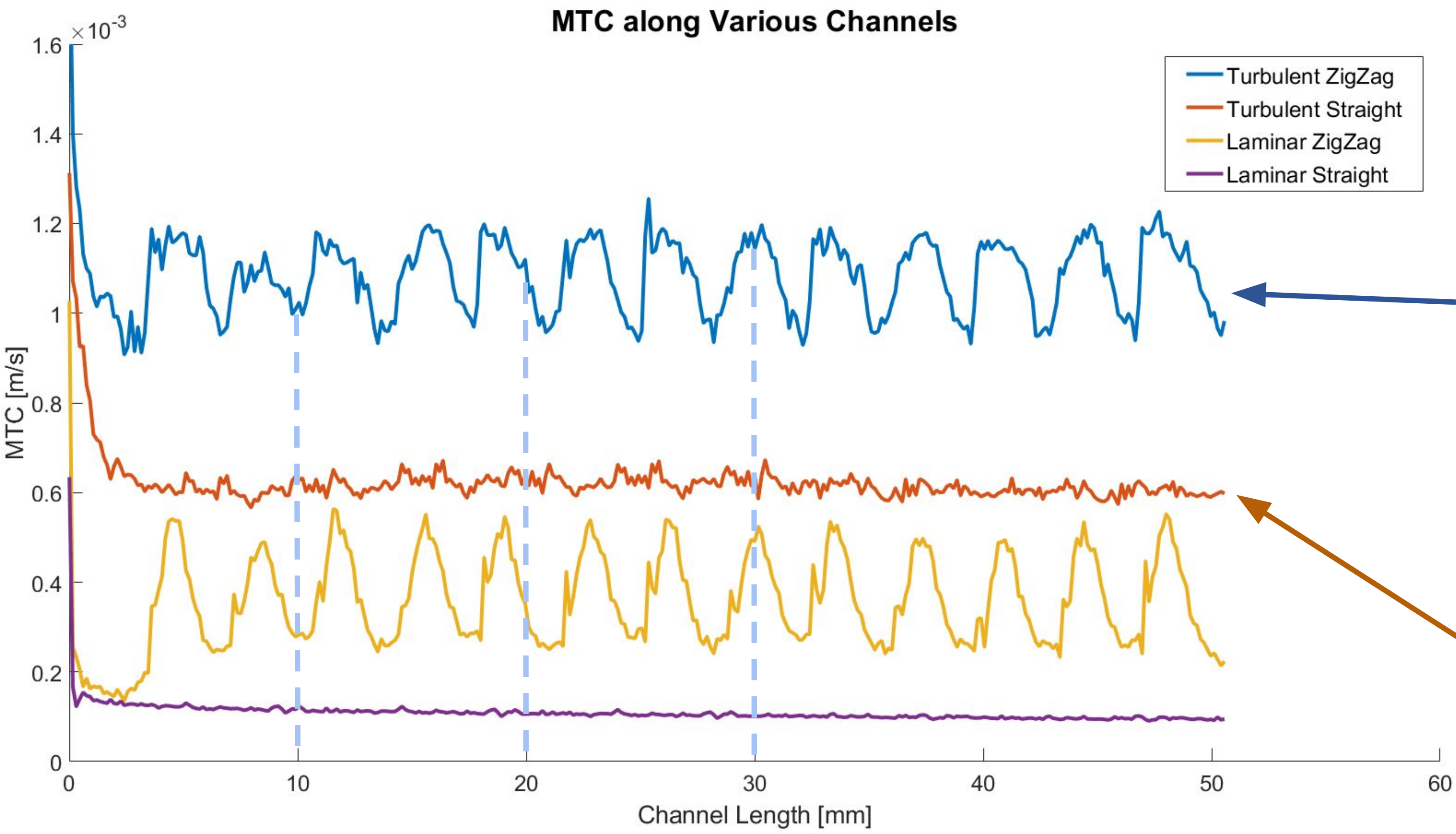


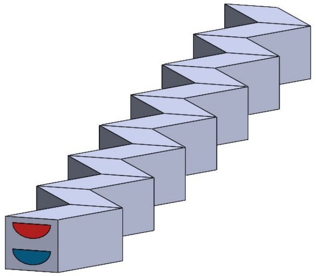
$$MTC_{Convective} = \frac{q_{FLiBe\ to\ Metal}}{C_{FLiBe\ Bulk} - C_{FLiBe-Metal\ Interface}}$$

Velocity to MTC Comparison

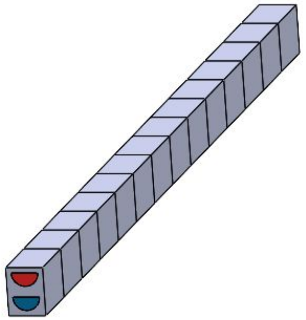


Laminar vs Turbulent Cases





'Zigzag'



'Straight'

Main Takeaways and Future Steps

- Turbulence Enhances Tritium Transport
  - Increases convective transport
- ZigZag Geometry Enhances Tritium Transport
  - Pushes fluid to higher speeds, enhancing convective transport
    - Pressure Drop up to ~8MPa → Pumping Power Issues
- Other Parameters of Consideration
  - Different Bend Angles for ZigZag Channel
  - Orientation of Channels
  - Metal Properties
  - Different Geometries
    - Twine, Gyroid, etc.

Bonus Slides

1. Project One-pager
2. Existing methods of tritium extraction
3. PAV designs
4. Types of heat exchangers
5. More on PCHE
6. Diffusion bonding
7. Gyroid HX
8. Selection of velocities for turbulence and laminar
9. Residuals Plots
10. Mesh setup
11. Simulation Mesh Independence Study
12. Equations Sheet

Optimizing Tritium Recovery with Commercial Heat Exchangers to Advance Commercial Fusion Energy

FUNG INSTITUTE FOR ENGINEERING LEADERSHIP
UC BERKELEY ENGINEERING

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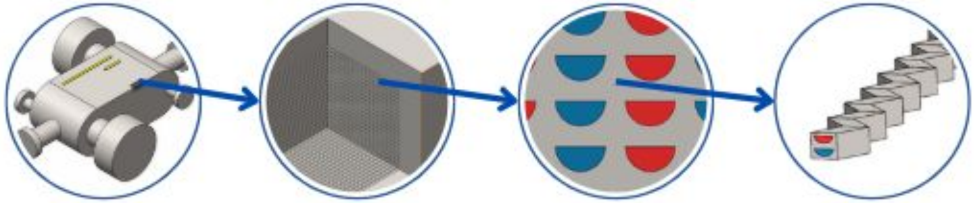
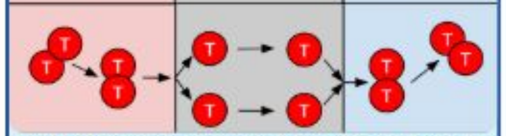
Advised by Professor Guanyu Su and Ben Li

Tritium is a fuel source for nuclear fusion devices. Manufacturing tritium is highly expensive as it is produced typically in nuclear reactors, so modern fusion energy devices utilize molten salt to produce tritium. The issue comes from extracting that tritium out of the salt such that it can be used for future fuel cycles. Our team is using computational fluid dynamics software to analyze various heat exchanger designs to determine a cost-effective method of tritium extraction from such molten salt.

What We Are Simulating



Main Physics



Much of the tritium is in the salt, of which the resulting **concentration gradient drives tritium diffusion** from the salt into the vacuum, **splitting** and **recombining** along the way. The steel acts like a **filter** for the tritium.

Where Our Role Comes In

Tritium is produced in a molten salt as a result of neutron bombardment from the deuterium-tritium reaction in a fusion device

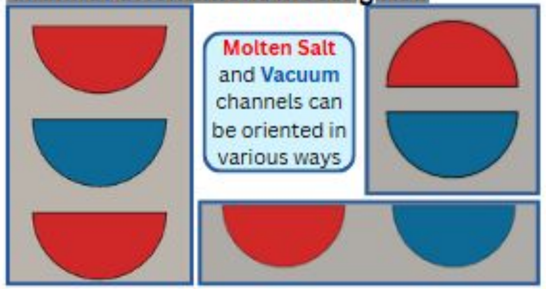
↓

Molten salt enters the **heat exchanger where tritium diffuses into a vacuum chamber**

↓

Extracted tritium is used for future fusion device fueling

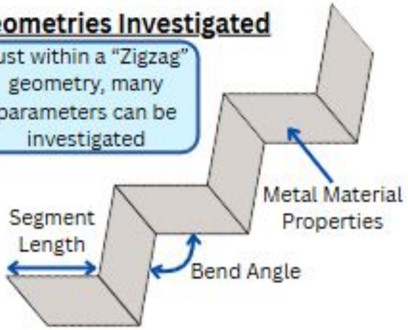
Channel Orientations Investigated



Molten Salt and **Vacuum** channels can be oriented in various ways

Geometries Investigated

Just within a "Zigzag" geometry, many parameters can be investigated



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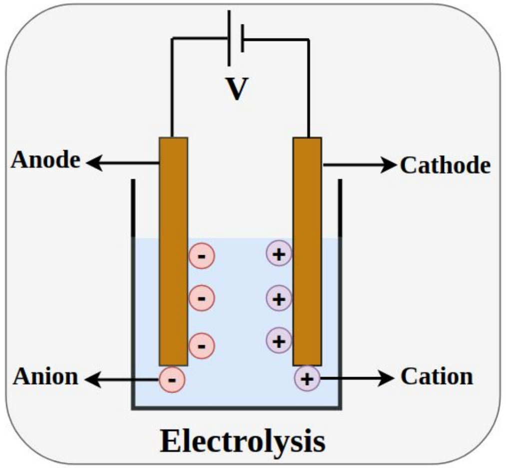
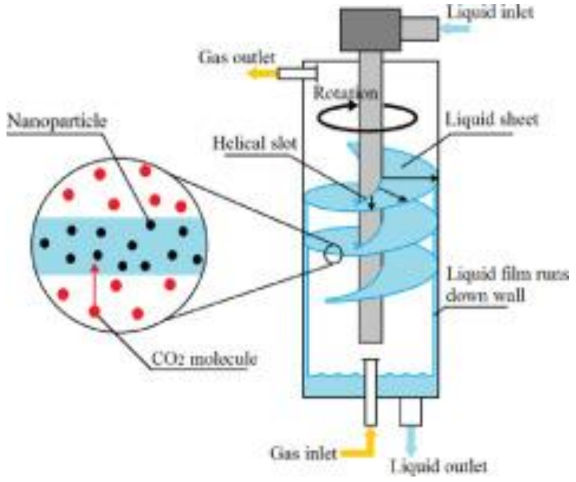
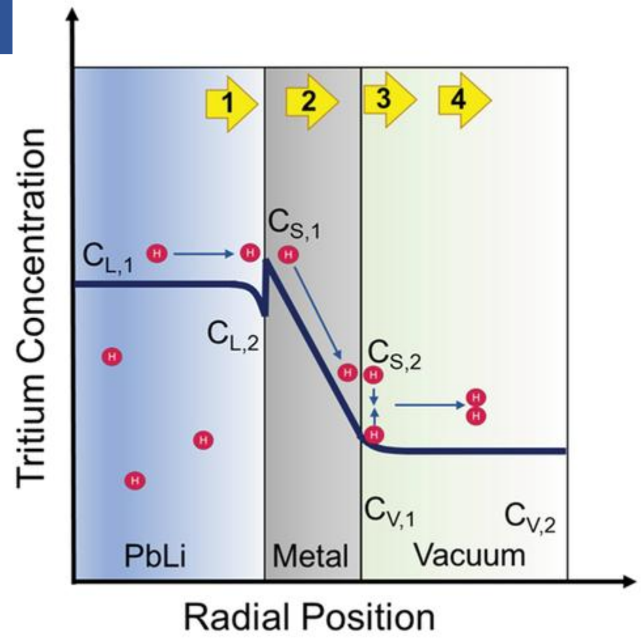
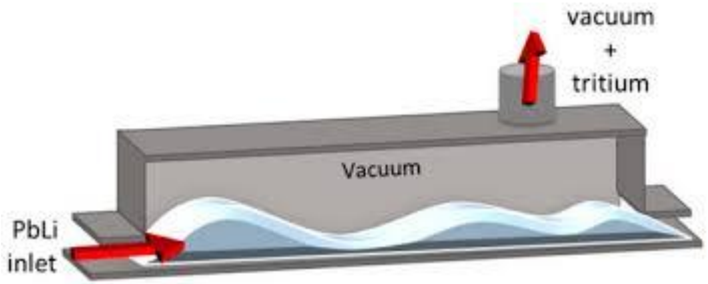
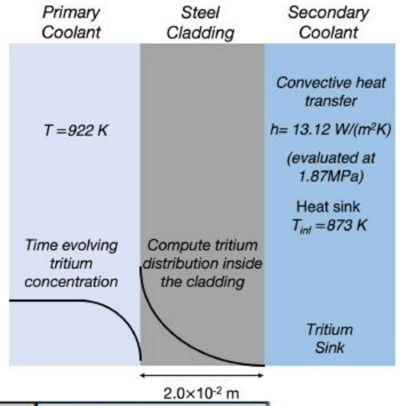
Current methods of tritium extraction

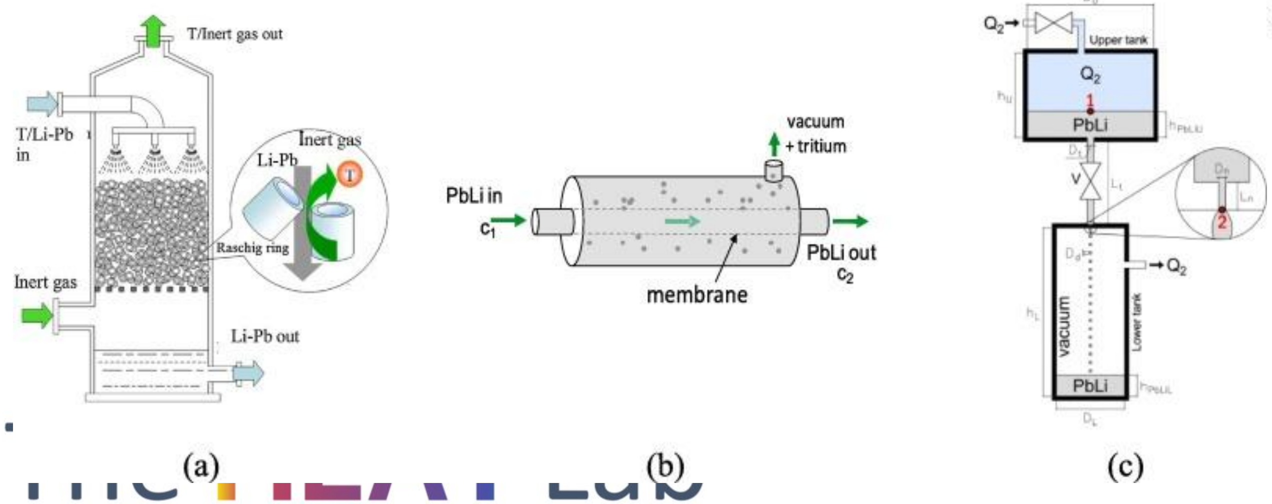


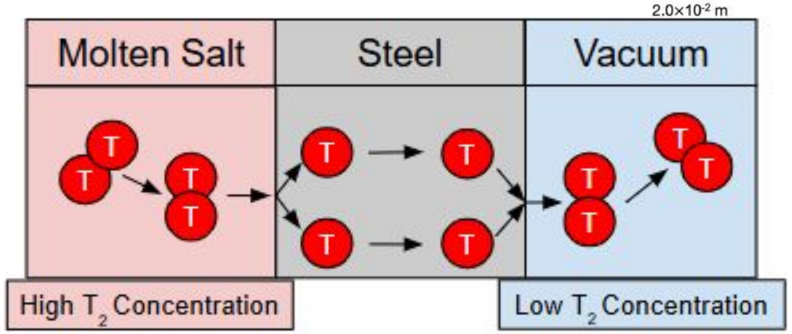




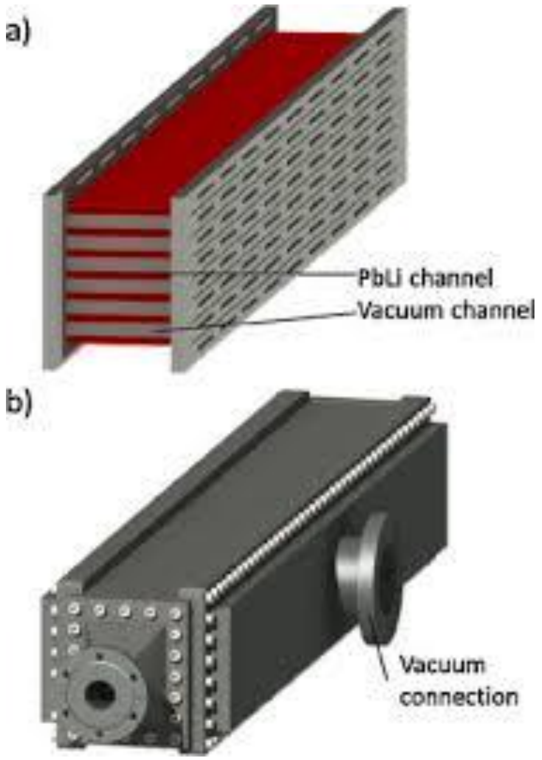


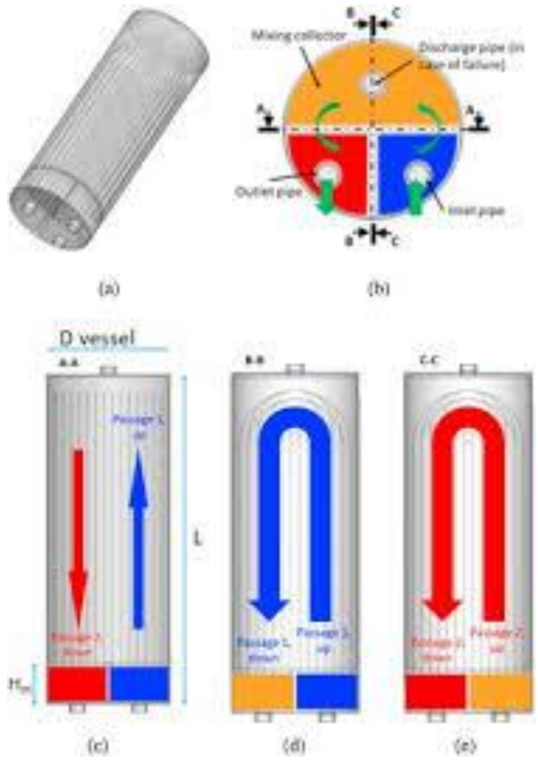


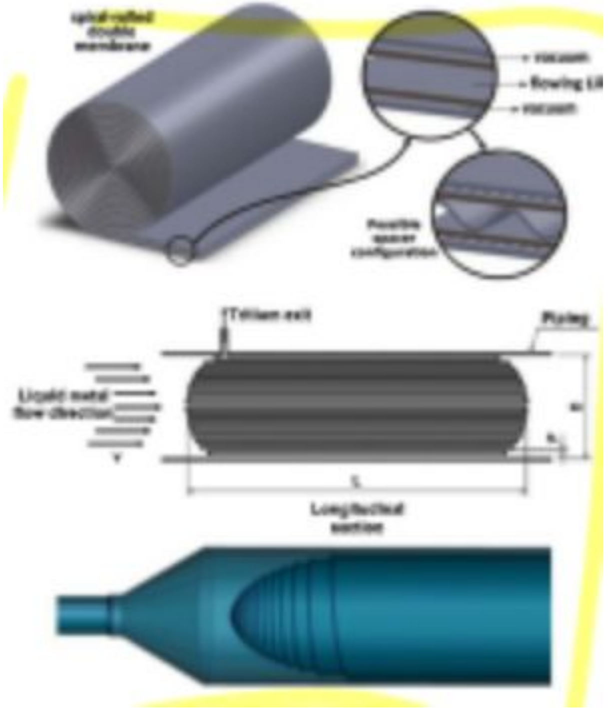




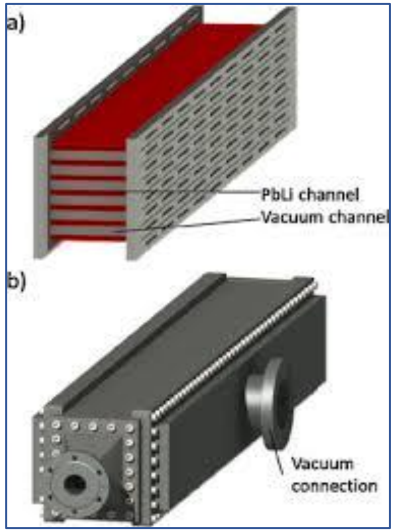
Existing PAV Designs

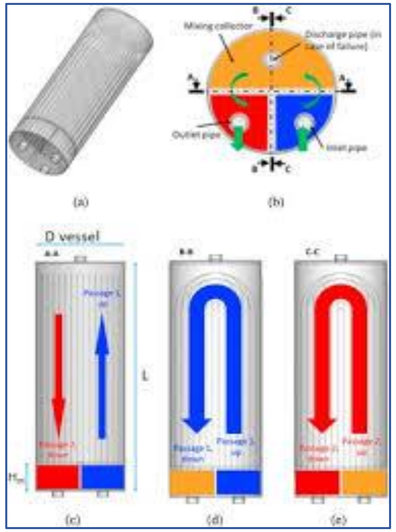






Existing PAVs and the potential of heat exchangers





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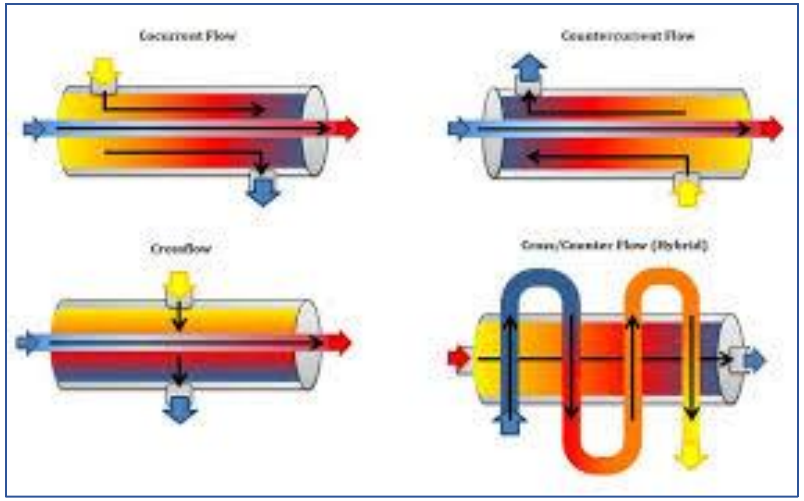

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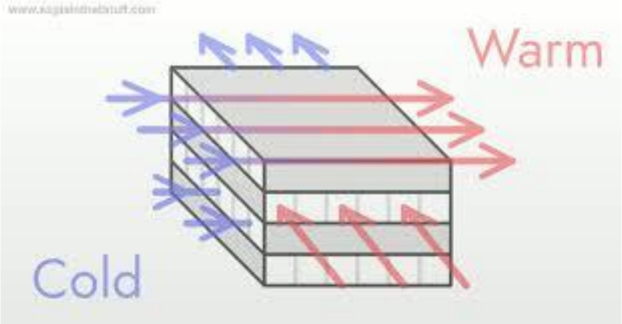
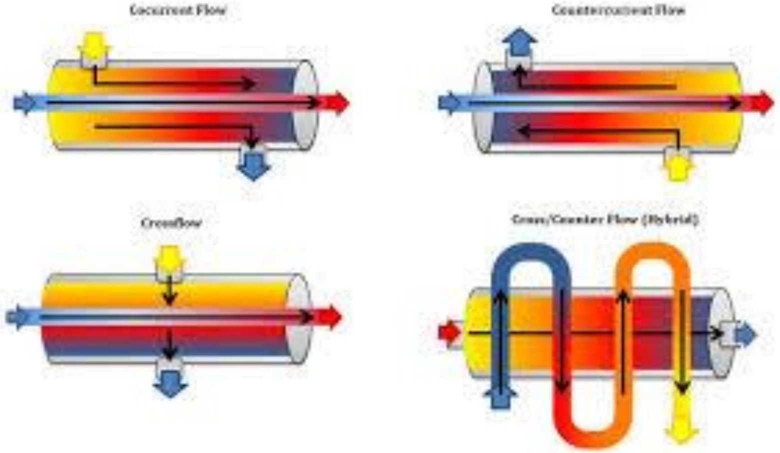
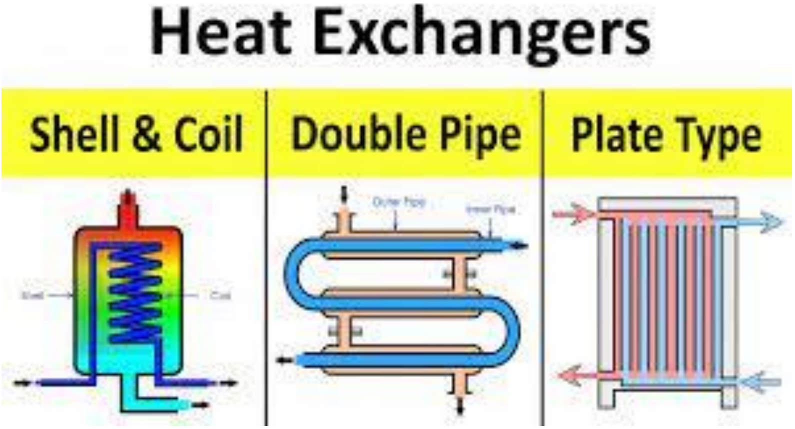
The potential of heat exchangers

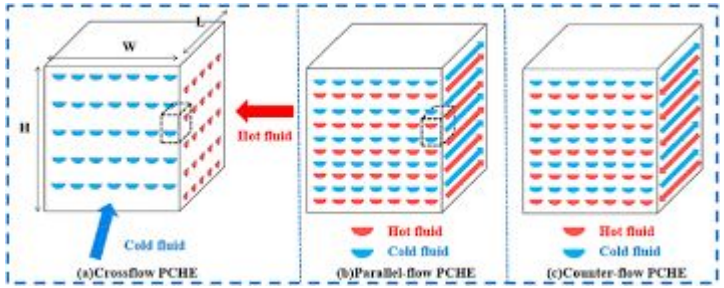


a) Typical design of PCHE for concentrated solar power plants

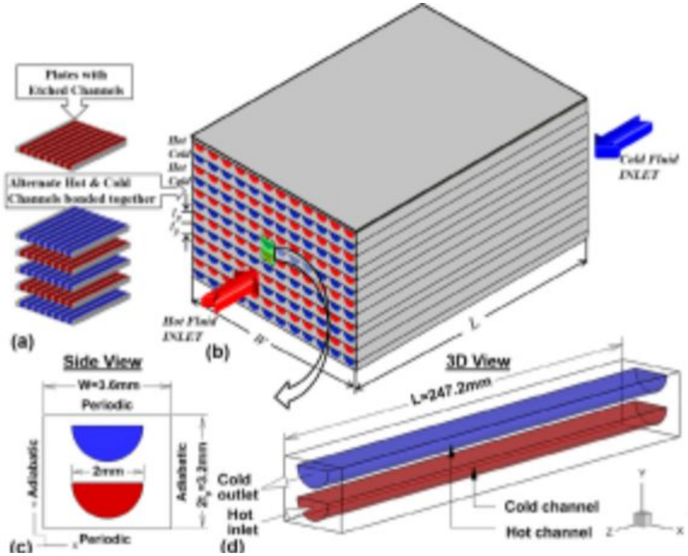
b) Cutaway image of straight-channel PCHE with headers and flanges attached [3]

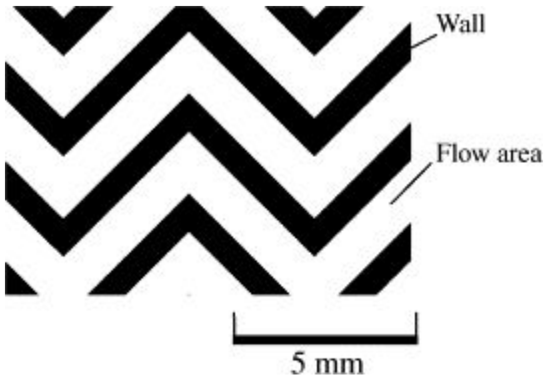


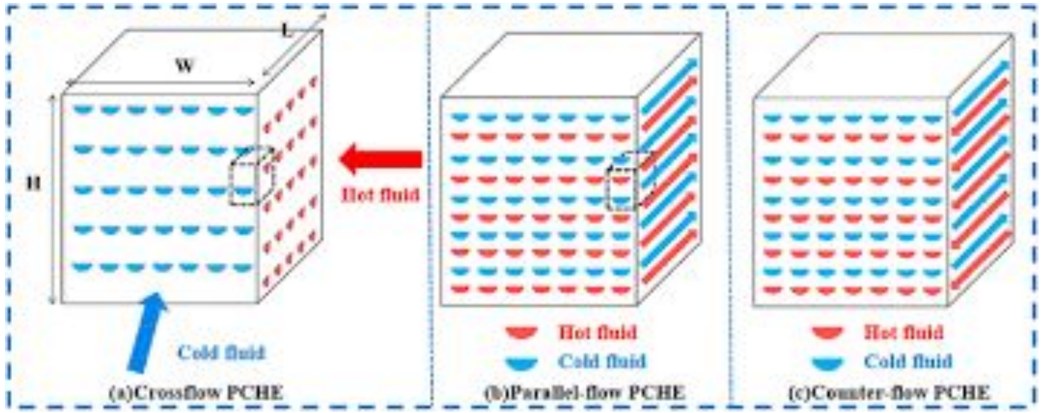


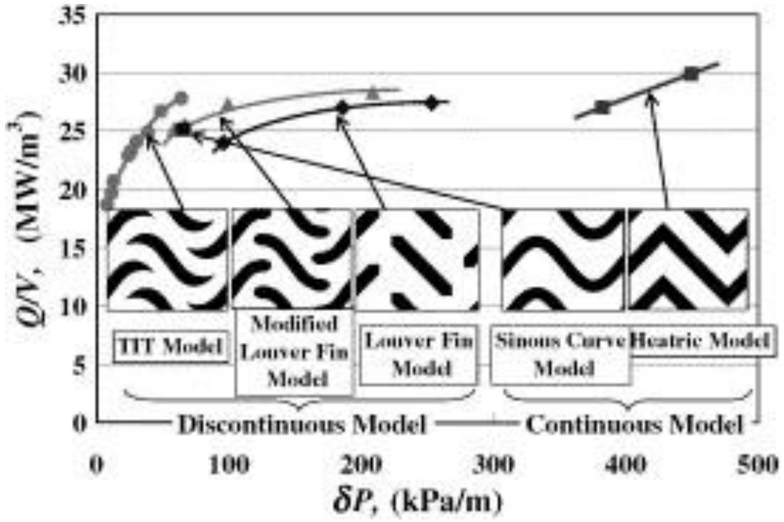


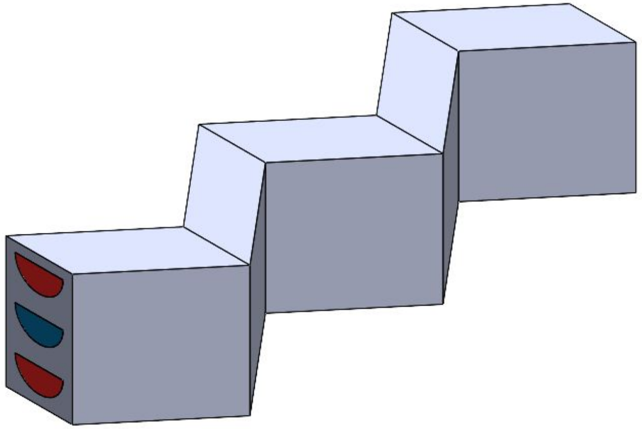
Printed Circuit HX's







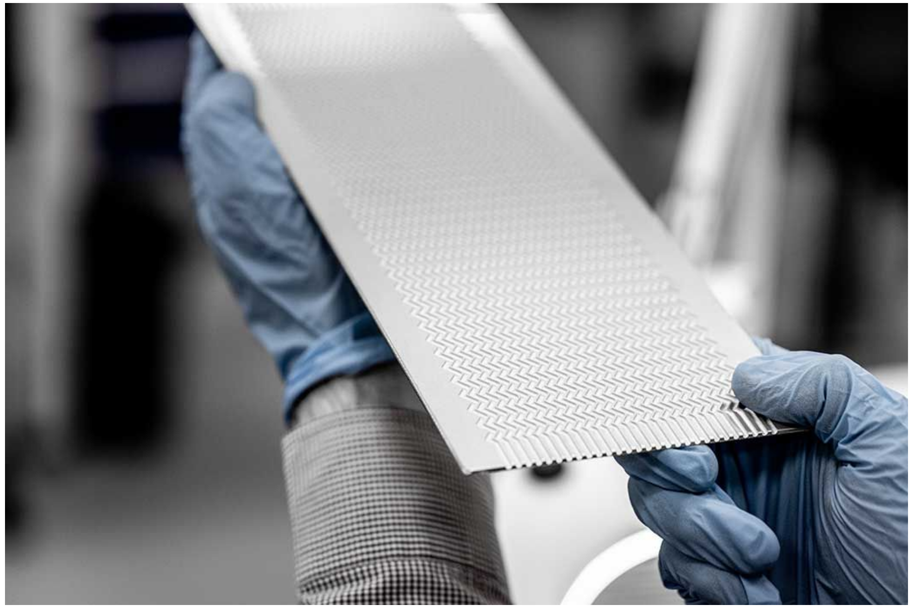




materials used
geometry (zig-zag) and scale

b

Printed Circuit Heat Exchanger



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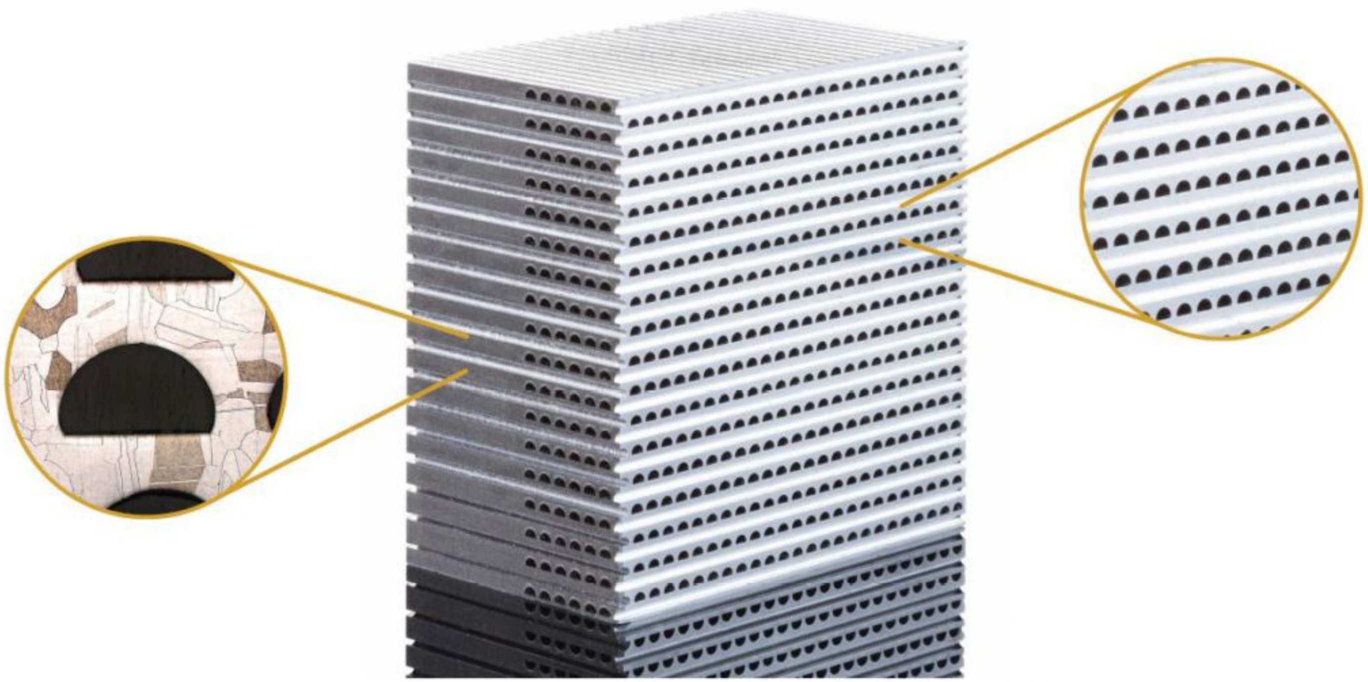
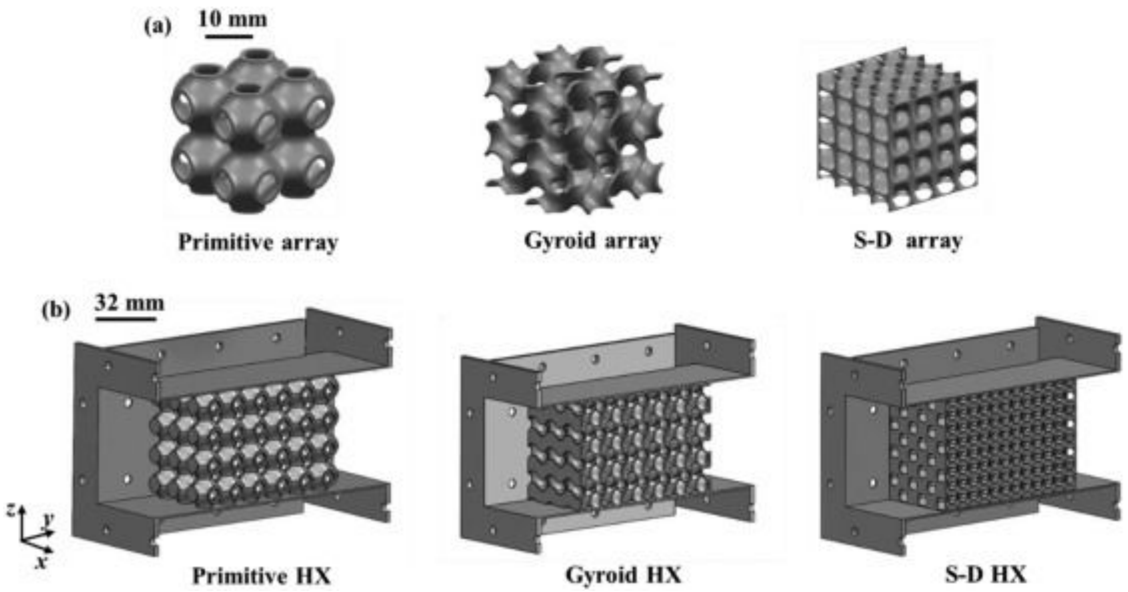
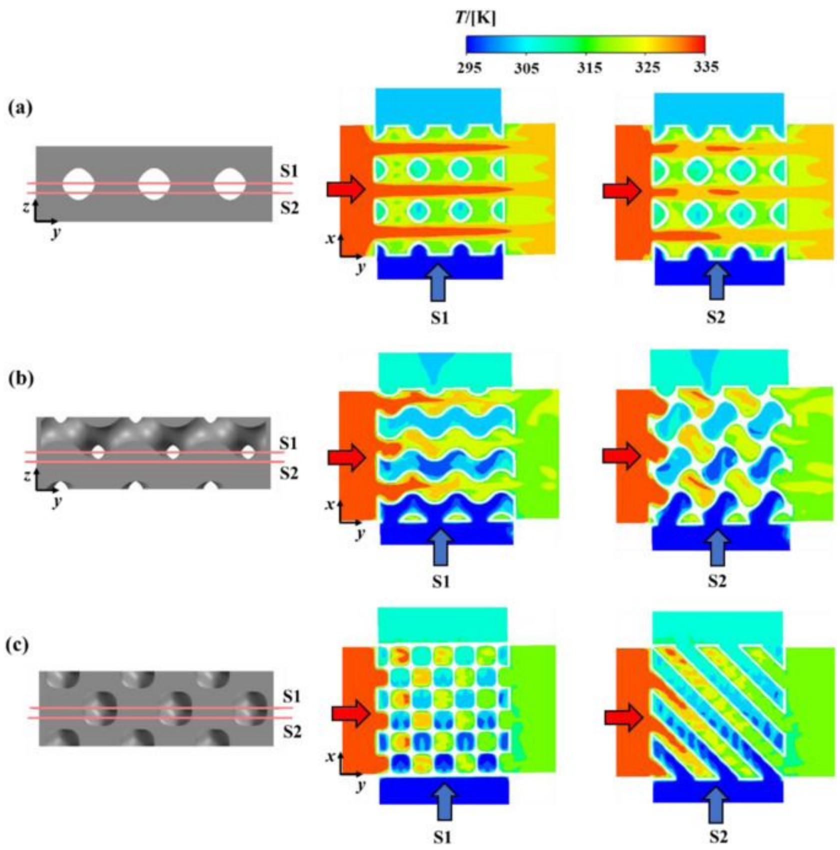
Grain Structure



Gyroid HX



(a)
10 mm
Primitive array
Gyroid array
S-D array
(b)
32 mm
Primitive HX
Gyroid HX
S-D HX



T/[K]
295 305 315 325 335
(a)
(b)
(c)
S1
S2

Velocity Calculations

what's a reasonable pressure drop?

do we need to account for FULL length of pche channel?

determine pressure drop for current segment

velocity (m/s)	pressure drop (Pa)	pressure drop (atm)	length of current channel [mm]
15	7.93E+06	78.28	36.68

hows this pressure compare to actual PAV designs in literature?

Ngo et al. [20] e	2-12 MPa	Heat transfer and frict	745.20
Kim et al. [21] nu	2.5-8.3 MPa	^	846.00
Pidaparti et al. [2	7.5-10.2 MPa	^	500.00
Thus, it is neces	20 MPa		https://www.osti.g

if we are to determine total pressure drop over entire heat exchanger length, ho

we are currently simulating 36.68mm or 0.036m which isn't a lot. but how much

is it easier to just analyze behavior of mass transport in turbulent and then lamin

^just need to choose a velocity that ensures one or the other. 15m/s ensures tur

flibe conduct velocity — u = velocity, solving for u

flibe mass flow [kg/s] and [m3/s]	2131.868	1.08
flibe inlet density @T=908.15K [kg/m3]	1969.823	
area of flibe tube from reactor (possibly divided by 18 fo	0.00000141764	
number of conducts (to be decided)	200,000	<<----independent
velocity inlet for single conduct [m/s]	3.817	
u = [m/s]	6.931	<---- any velocity l

maybe just do as guanyu suggested and just test a velocity that ensures laminar zone

Reynold's Numb

RE = uD/v	u = velocity	solving for u	
	D = hydraulic dia	D = 4A/P = ------------	0.001099828
	v = dynamic visc	---------------------------	0.000003811
	Re = (maximum for guarenteed laminar)		
	2000		
	u = [m/s]		
	6.931	<---- any velocity lower than this would be laminar	

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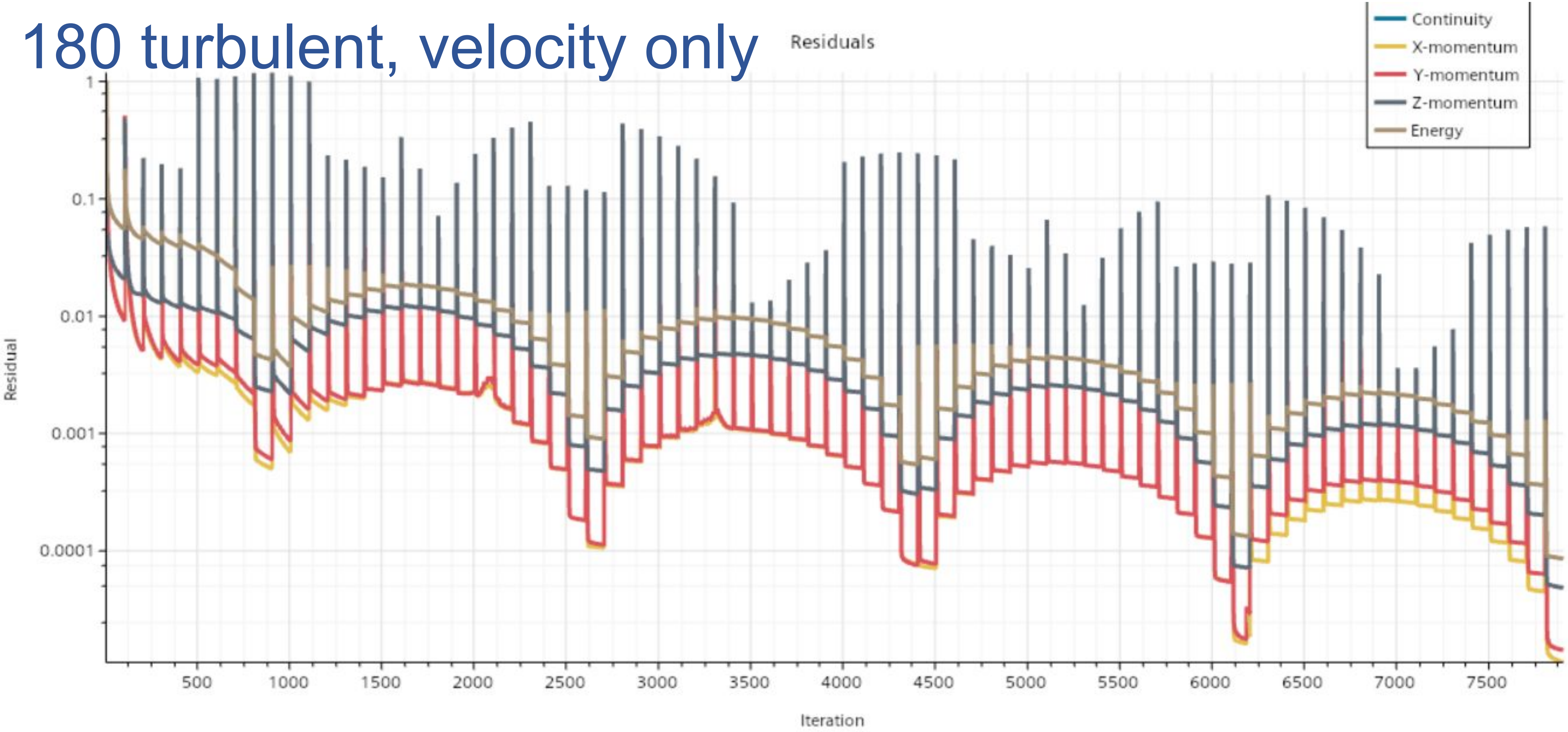
180 turbulent, velocity only



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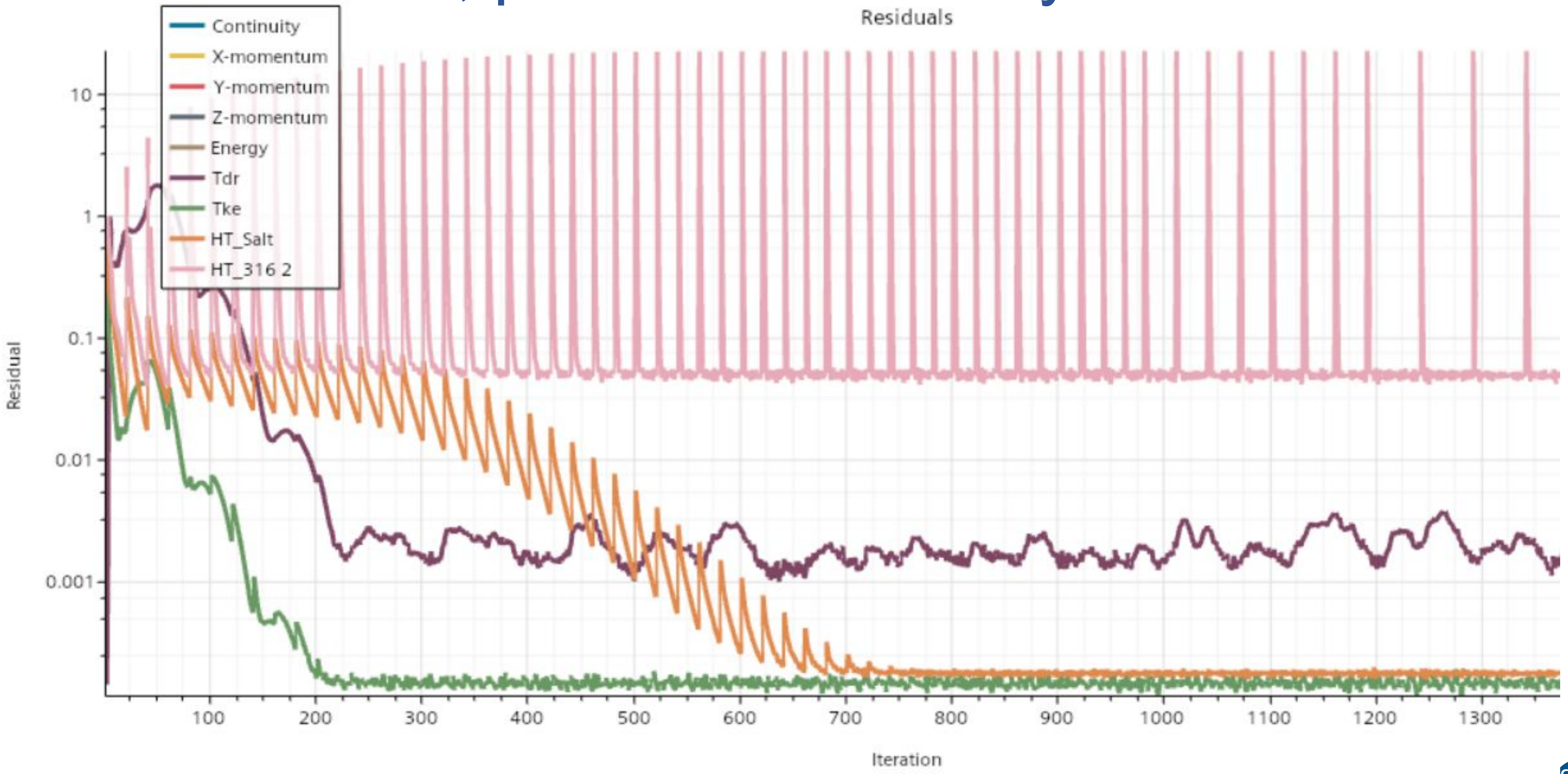
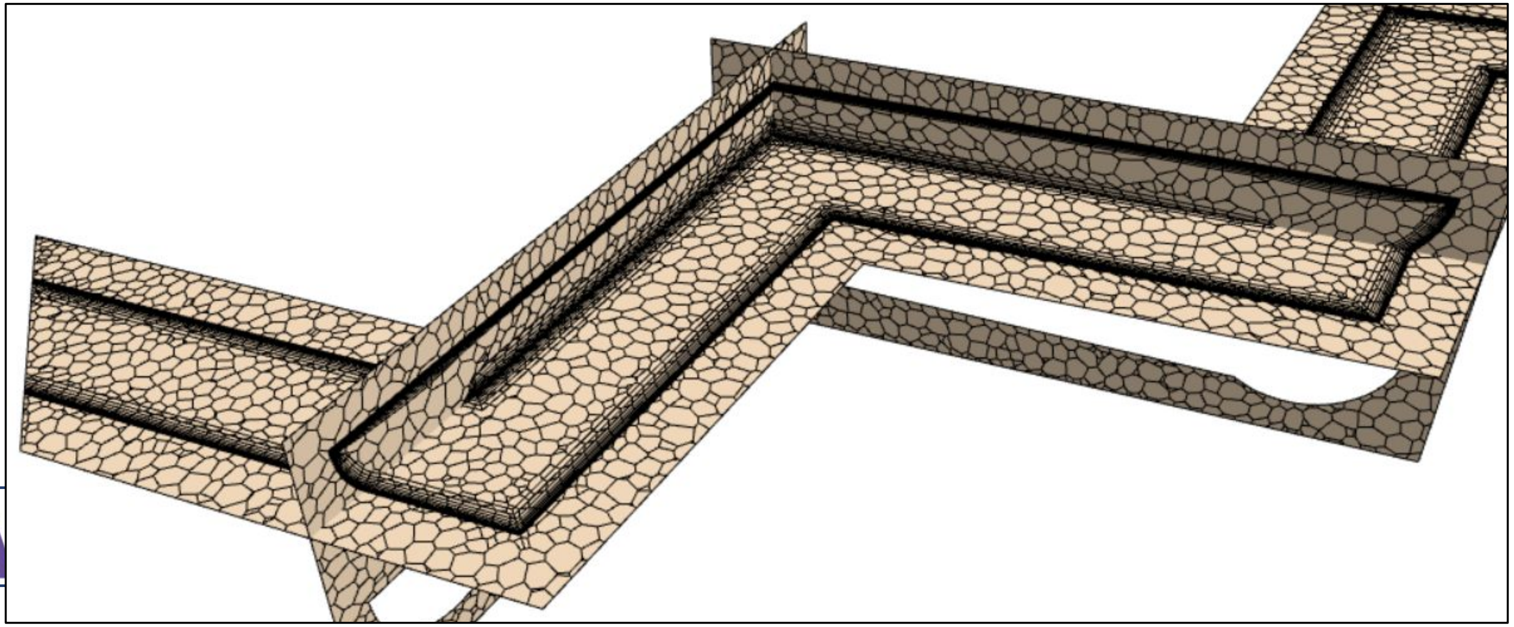
100 turbulent, passive scalar only



Meshing Setup - Polyhedral Mesher

FLiBe
- base size = 0.3 mm
- surface growth rate = 1.2
- prism layers = 10
- prism layer stretching = 1.2

316SS
- base size = 0.5 mm
- surface growth rate = 1.2
- prism layers = disabled



Simulation Mesh Independence Study

Simulation Strategy/Procedure

2 Main Steps:

- 1) Simulate only the flow
    - extract “steady-state” velocity field
- 2) Simulate passive scalar
    - set static velocity field for the passive scalar to follow