Scoping Study of He-cooled Porous Media for ARIES-CS Divertor

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He-cooled divertor concepts

A number of possibilities are available:

- Simple pipe/tube
  - micro-channels would be an extension of this design
- Porous medium
- Other heat transfer enhancement technique
  - e.g., pins, fins, fibers

UCSD collaborating with GA Tech

- General scoping of different divertor concepts
- Preliminary results of a porous media concept are shown here

He-coolant with porous media divertor concept

We focused our initial efforts on porous media because we have the tools for it at UCSD

- MERLOT is a porous media heat transfer code that we began developing at UCSD several years ago

These preliminary results are for isotropic porous media

- For sake of simplicity
- However, we do believe that ***tailored porous media*** has an advantage to improve heat transfer performance for a given pressure drop penalty.

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Analysis of porous media

Desired characteristics of a heat transfer code

- Variable local porosity and characteristic dimension (local variation of microstructure)
- Non-isotropic solid thermal conductivity
- Radial thermal dispersion
- Variable local ***h*** between solid and fluid
- Temperature dependent thermal conductivity of solid and fluid
- Ability to apply heat flux and/or volumetric heat generation

The **M**odel of **E**nergy transfer **R**ate for f**L**ow in **O**pen porosity **T**ailored media,

(MERLOT) was developed based on these needs.

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Calculation procedure of MERLOT

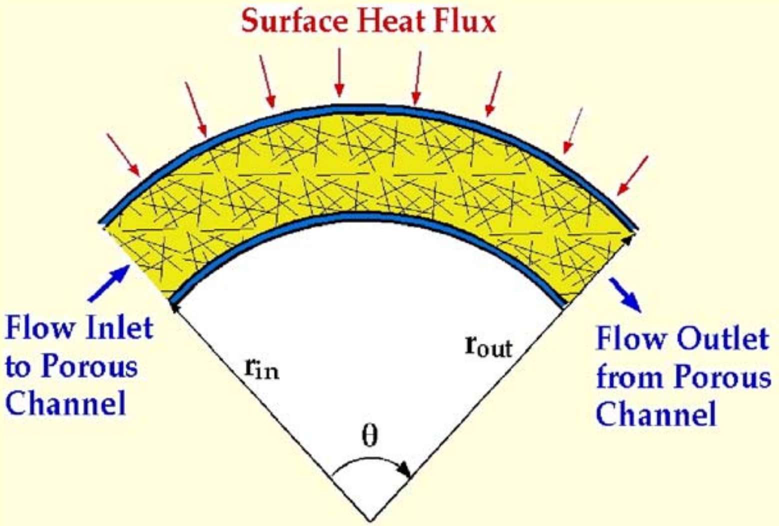
1. The He mass flow rate corresponding to a given He temperature rise and a given heat input is calculated.

2. The pressure gradient, corresponding to the calculated He mass flow rate, average porosity, and particle diameter is estimated from the Ergun equation for a packed bed:

$$\frac{dP}{dx} = 150\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu V_0}{(\varphi d_p)^2} + 1.75\frac{(1-\varepsilon)}{\varepsilon^3}\frac{\rho_f V_0^2}{\varphi d_p}$$

3. The correct 1-D velocity profile corresponding to this pressure gradient and to the porosity spatial distribution is then computed.

4. Finally, the corresponding 2-D temperature distribution in the solid and fluid is calculated, yielding the exact He outlet temperature.



Modified Darcy Equation (θ direction):

(1-D based on average ρ)

$$0 = -\frac{1}{r}\frac{\partial P}{\partial \theta} - \left(\frac{\mu}{K}\right)v_\theta - \left(\frac{\rho_f c_F}{\sqrt{K}}\right)v_\theta^2 + \mu_{eff}\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(r v_\theta)\right)\right]$$

2-d Energy Equation (r,θ):

Solid: $$0 = (1-\phi)\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r k_{s,r}\frac{\partial T_s}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \theta}\left(k_{s,\theta}\frac{\partial T_s}{\partial \theta}\right) + q'''_s\right) + h_c S_{BET}(T_f - T_s)$$

Fluid: $$\rho_f C p_f \frac{V_\theta}{r}\frac{\partial T_f}{\partial \theta} = \phi\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r k_{f,t,r}\frac{\partial T_f}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \theta}\left(r k_{f,t,\theta}\frac{\partial T_f}{\partial \theta}\right) + q'''_f\right) + h_c S_{BET}(T_s - T_f)$$

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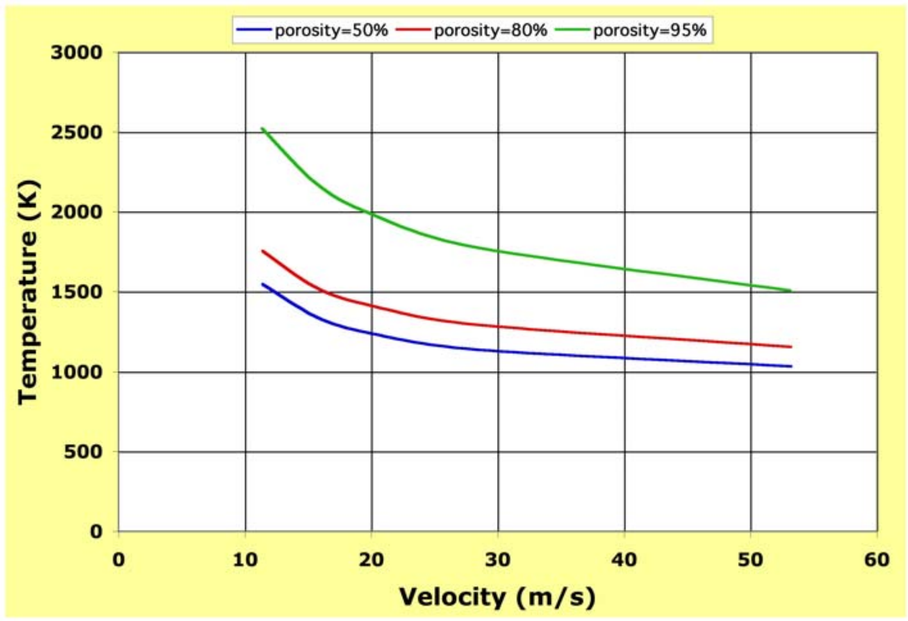
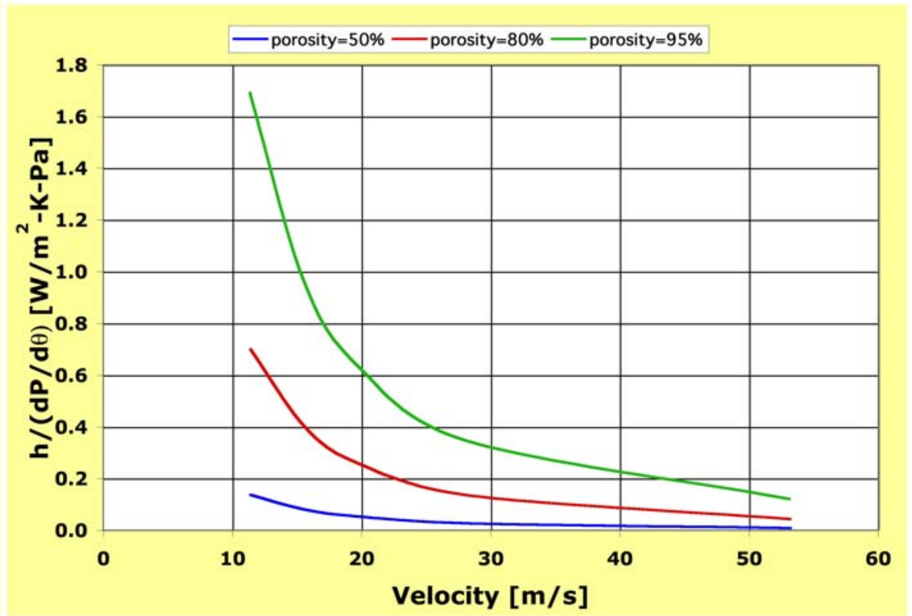
Lessons from previous studies using MERLOT

$q'' = 5\ MW/m^2 \quad d_p = 0.1\ mm \quad T_{in} = 823K$



High velocity is desirable for heat transfer performance…

$h_{eff}/(dP/d\theta)$ vs. velocity

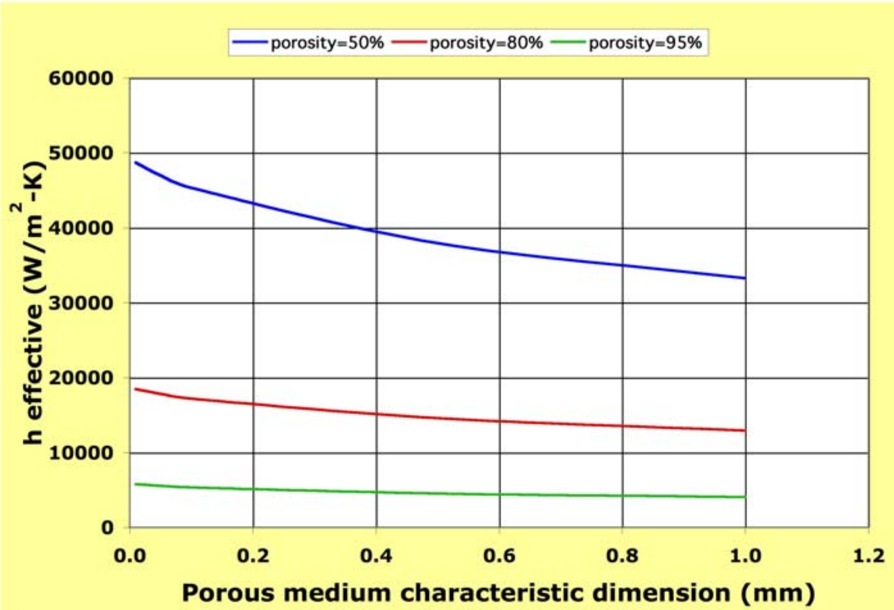


…but to alleviate pressure concerns, higher porosity is necessary.

MERLOT Lessons:
Effect of Porous characteristic dimension

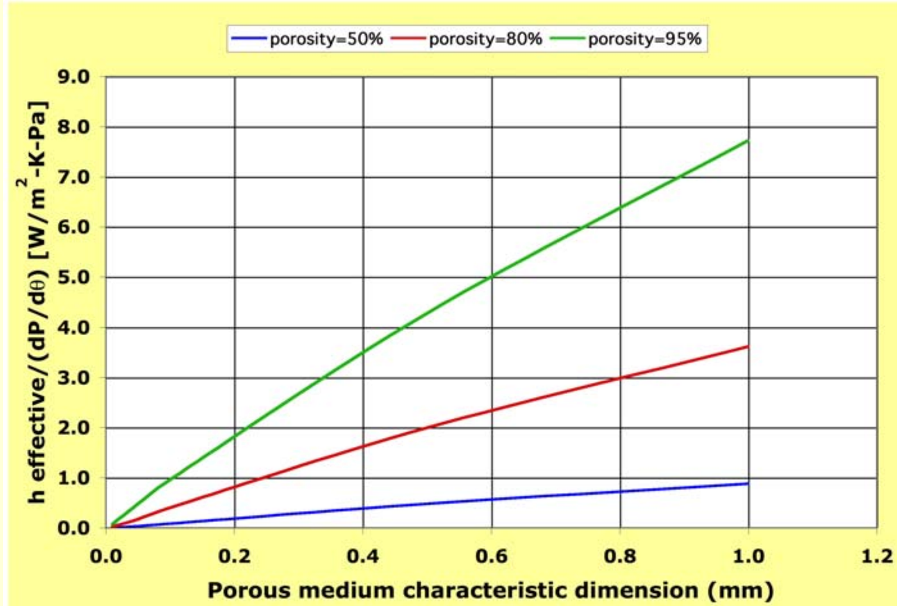
$q'' = 5\ MW/m^2$ $T_{in} = 823K$ $T_{out} = 1123K$

Surface area to volume ratio decreases with increasing $\boldsymbol{d_p}$, so drop in $\boldsymbol{h_{eff}}$ is expected.



$\boldsymbol{h_{eff}}/(dP/d\theta)$ vs. characteristic dimension, $\boldsymbol{d_p}$

Decreasing $\boldsymbol{d_p}$ results in major ΔP penalty.



For packed beds of spherical particles, there is not much that can be done to make this better.

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The porous medium must have more design flexibility (e.g., tailored foam structures or fibers).

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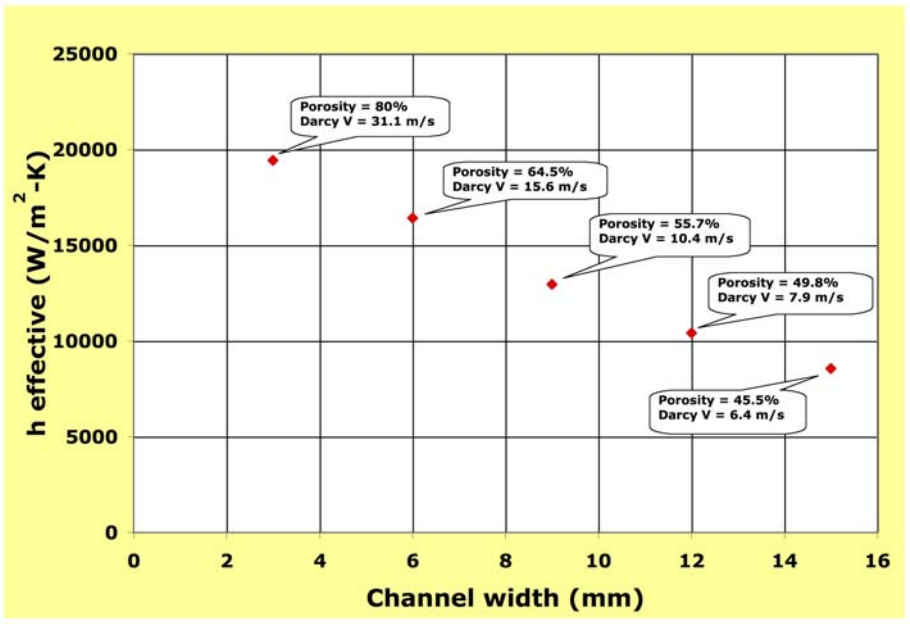
MERLOT Lessons:
Smaller channel width is better

$q'' = 5\ MW/m^2$ $T_{in} = 823K$, $T_{out} = 1123K$ $r_{out} = 24\ mm$ $d_p = 0.15\ mm$

h_{eff} vs. channel width



For a constant pressure drop and constant He mass flow, narrower channel width provides better h_{eff} at ***higher velocity and higher porosity***.

(The porosity is adjusted higher to offset pressure drop increases due to higher velocity at smaller channel sizes)

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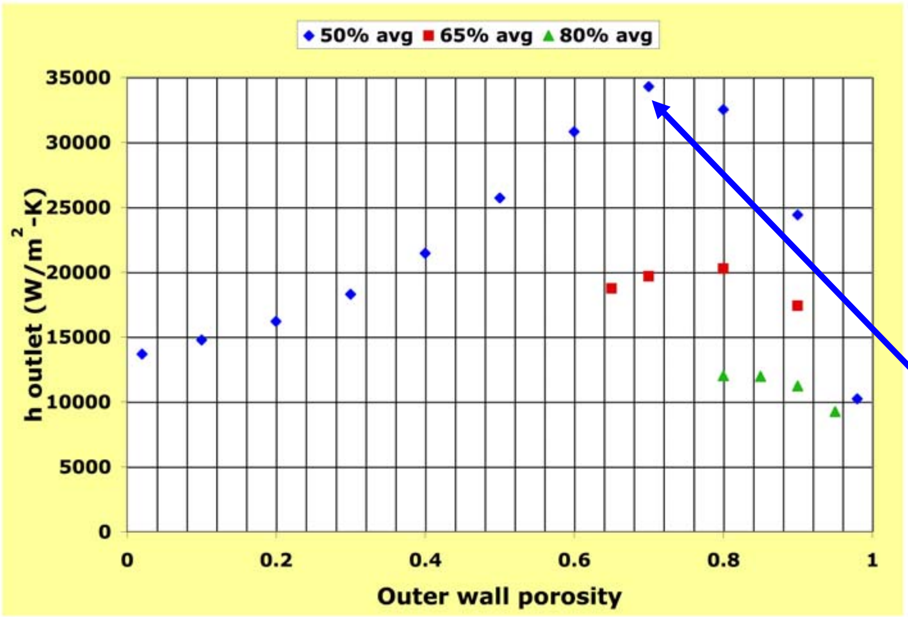
Local porosity variation effects

$q'' = 10\ MW/m^2$ $T_{in} = 823K$, $T_{out} = 1223K$ $r_{out} = 12\ mm$ $d_p = 0.05\ mm$

***h**$_{eff}$* vs. outer wall porosity



Porosity varies linearly from the inner to outer wall. Average porosity is shown.

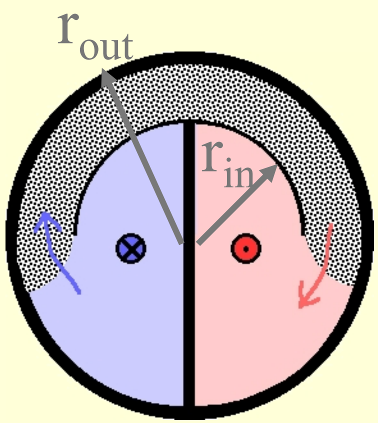
Is there an optimum radial porosity profile that would maximize heat transfer performance?

We tried linearly varying profiles and found a maximum ***h**$_{eff}$*.

The 70%-30% case is most evident.

(avg. = 50%).

ARIES-CS divertor application



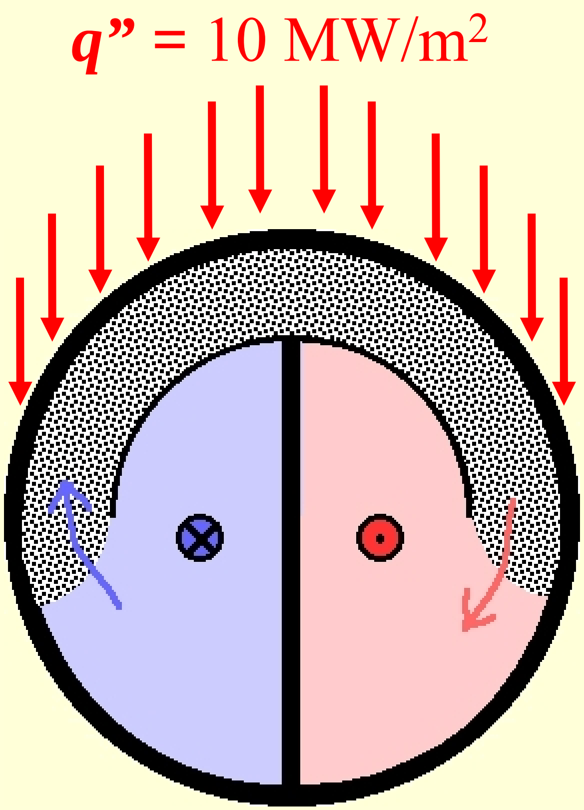
Approach to size the tube (constrain pressure drops):

- Specify inner radius, $\boldsymbol{r_{in}}$
- Place a <u>constraint on the inlet plenum pressure drop</u> (0.25%$\boldsymbol{P_{in}}$)
- Find the max He mass flow rate available that meets the constraint
- Place a <u>constraint on the porous medium pressure drop</u> (5% $\boldsymbol{P_{in}}$)
- For each ε and $\boldsymbol{d_p}$ combination desired, use Ergun eqn. to find the maximum $\boldsymbol{v_{ref}}$ that meets the porous pressure constraint
- The minimum porous cross sectional area, $\boldsymbol{A_p}$, can be calculated and subsequently we find $\boldsymbol{r_{out}}$
- Using the mass flow of He and the applied heat flux, ***q”***, we find the temperature increase of the helium, $\boldsymbol{\Delta T_{He}}$
- Run MERLOT to find the maximum wall temperature, $\boldsymbol{T_{wall,\ max.}}$

Divertor sizing calculations

- Inlet plenum constraint: 0.25%P_{in}
- Porous medium constraint: 5% P_{in}
- ΔT_{He} based on q'' =10 MW/m^2

r_{in} (mm)	r_{out} (mm)	ΔT_{He} (K)
20	29.10	234
15	18.64	323
12	13.78	437
11	12.34	492
10	11.00	564
9	9.71	666
5	5.11	1695



ε=80%, d_p=0.5mm, P_{in}=5 MPa, L=0.5m

NOTE: For d_p=0.5mm, the final rows of the table are not realistic.

At least 10 particles across δr is desirable.

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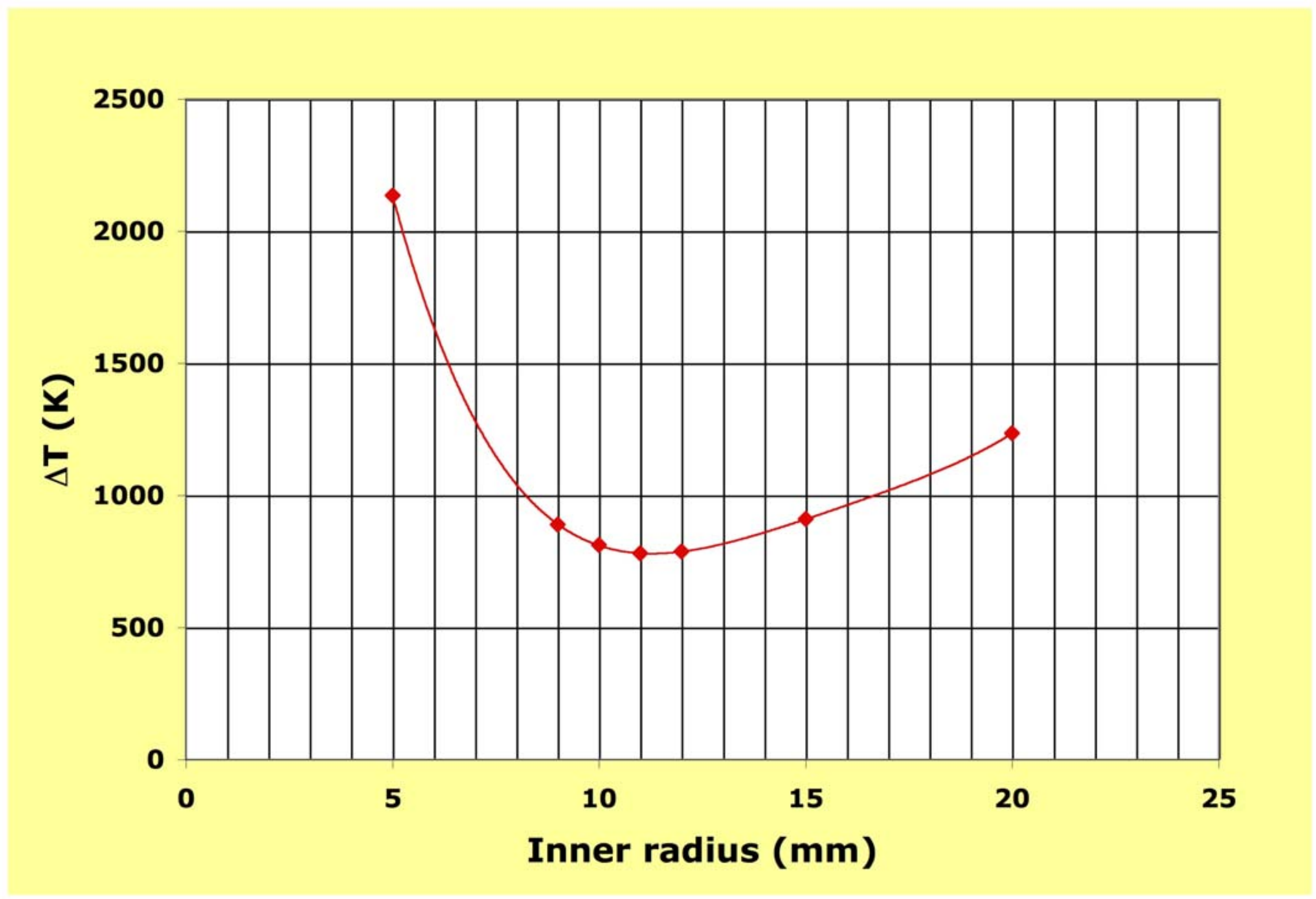
Using the pressure drops in the open tube and the porous medium as constraints, an optimum inner radius, r_{in}≈11mm, is found for the design.



ΔT on the figure = ($T_{wall, max}$ - T_{inlet})

Example calculation for a 10 MW/m^2 divertor design

•From the previous calculations, $\boldsymbol{r_{in}}$ = 11 mm looks like a good place to begin.

•We decide to fix $\boldsymbol{r_{out}}$, however, so that we can fit 10 porous particles for the chosen $\boldsymbol{d_p}$.

•Inlet temperature is chosen based on a Tungsten design.

r_{in} = 11 mm
r_{out} = 14 mm
d_p = 0.3 mm
ε = 80% and 60%
T_{in} = 650 ^{0}C
q'' = 10 MW/m^2
T_{out} = 700 ^{0}C, 750 ^{0}C, 850 ^{0}C, 950 ^{0}C

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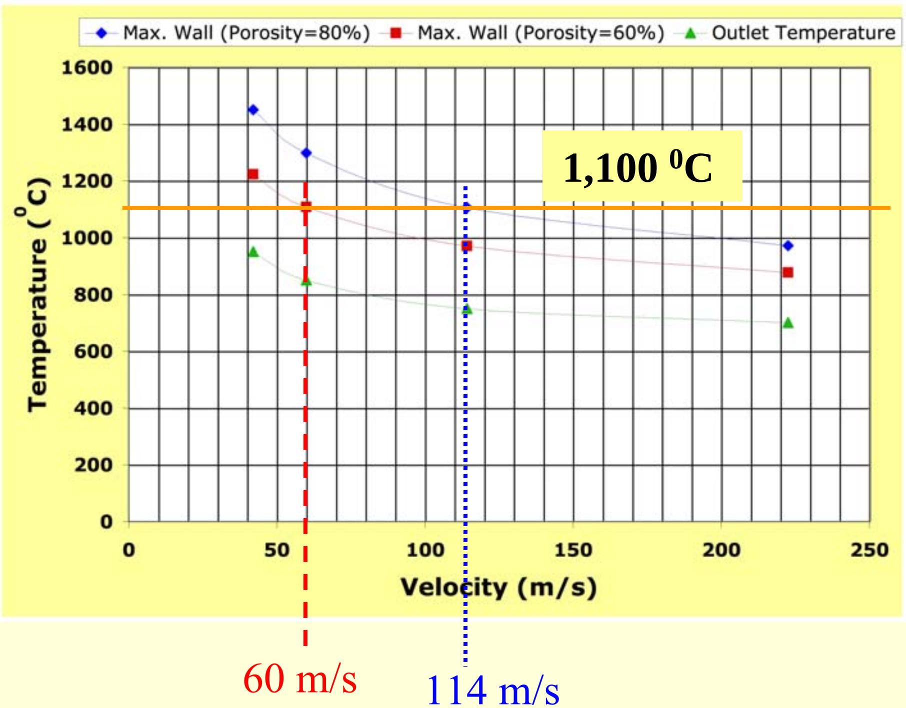
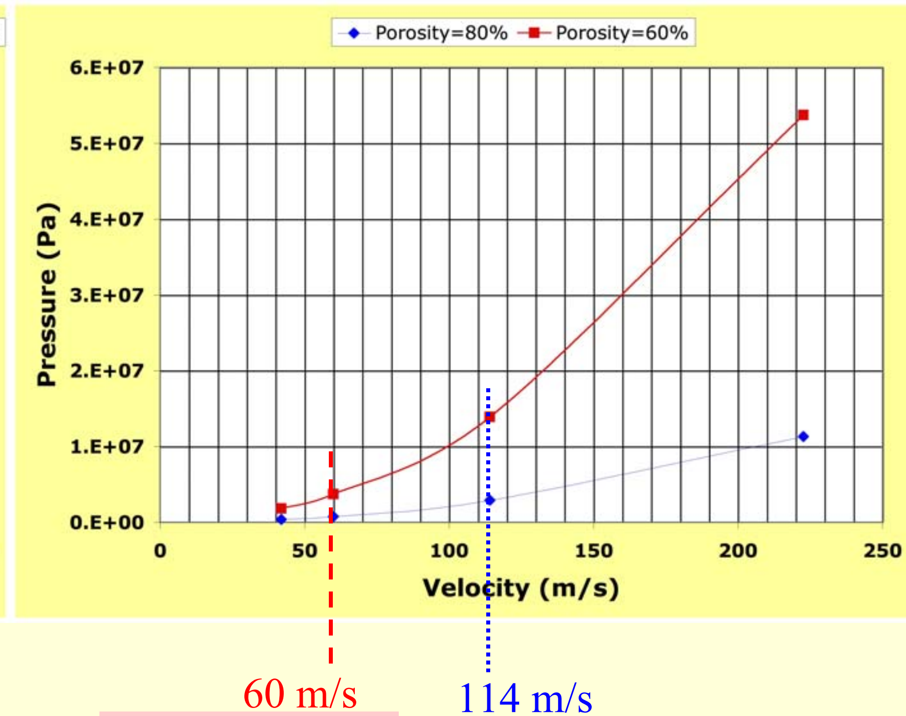
Velocity & Pressure results for 10 MW/m² example

Temperature limit based on 2 mm Tungsten wall
(assume 100 ^{0}C per mm; surface ≈ 1,300 ^{0}C)





ΔP = 3.7 MPa

ΔP = 2.9 MPa

To meet a **5%P_{in}** pressure drop limit, P_{in} would need to be **58 MPa** for the 80% porous design, and **74 MPa** for the 60% porous design.

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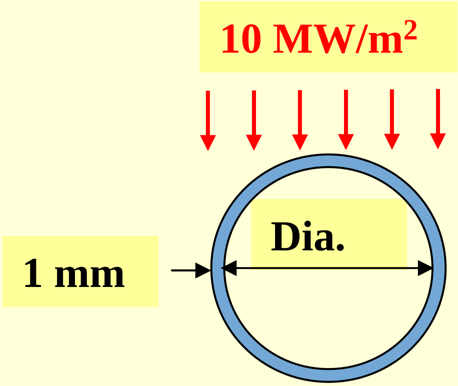
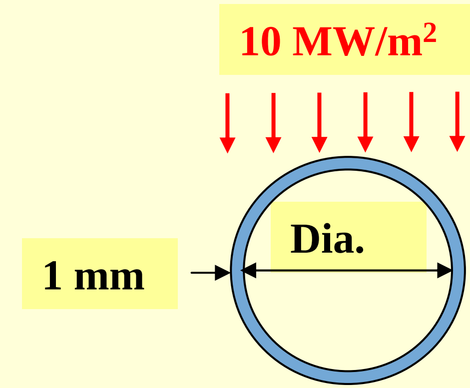
Example results for He flow in a regular tube of length 0.5 m: Pressure drop as a function of channel diameter and He temperature rise



ΔP= 0.4 MPa line shown assuming $\Delta P/P_{in}$~0.05 for example P_{in}=8 MPa

Example results for He flow in a regular tube of length 0.5 m illustrates the relative limitation of this simple configuration



Must be above ΔP= 0.4 MPa line to maintain $\Delta P/P_{in}$~0.05 for example P_{in}=8 MPa (from results shown in previous plot)

For tungsten T_{wall} < ~1000-1100°C, there is no solution

- Thus, simple channel configuration very limited in max. q'' that can be accommodated (<10 MW/m²)
- Perhaps very short microchannels would help, but very challenging

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Summary and Future Work

- By relaxing the pressure drop constraint a bit, there is a workable porous tungsten design for 10 MW/m^2
  - We believe this design can be optimized somewhat with tailored local porosity and/or characteristic dimension.
  - The porous tungsten can then possibly be pushed to $\approx 12\ MW/m^2$.
- We can accept a somewhat higher pressure drop, but only if there are corresponding large gains in heat transfer performance.
- Future work would have to include more than optimization of local porosity and/or characteristic dimension.
  - The porous structure that is most attractive is one in which the heat conducts in a desirable direction with the least pressure drop penalty
    - Fibrous material
    - Pins/fins (this is essentially larger fibrous material)
    - Tailored foam?

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