SAND2015-4318C

Flow Instabilities in Refractory Metal, Porous Media, Helium-Cooled Plasma Facing Components

SP11-26

D.L. Youchison and R.E. Nygren

Corresponding author: Tel +1-505-845-3138; Fax +1-505-845-3130 E-mail: dlyouch@sandia.gov

Sandia National Laboratories, PO Box 5800, Albuquerque, NM 87185, USA

Abstract: Past numerical investigations of the performance of porous media to enhance heat transfer in helium-cooled devices neglected the susceptibility of multi-channel heat sinks to parallel flow instabilities even though experimental evidence suggests it may be a problem for narrow channel devices. In previous work, our simulations have shown that helium micro-jets do not experience changes in flow distribution due to non-uniform heating. However, jets are difficult to fabricate for large area refractory metal components. The same is not true for narrow channel devices filled with porous media. Although these refractory devices are easier to fabricate, the effects of downstream hot gas expansion can influence the incoming flow distribution in multi-channel configurations.

Computational Fluid dynamics modeling can reveal the subset of conditions that will lead to deleterious flow mal-distributions in multi-channel geometries containing porous media. Such phenomena rarely occur in devices with large channels made of high thermal conductivity materials, but are easily produced in small-channel refractory metal devices. In these devices, flow mal-distributions result from highly localized heat fluxes due to off-normal transient events or from non-uniformity in the heat flux profile at leading edges and divertor strike-points. Unfortunately, the nominal flow conditions compatible with efficient Brayton cycle power conversion favor the low flow rate, high delta-T devices that are most vulnerable to instabilities and flow bypass.

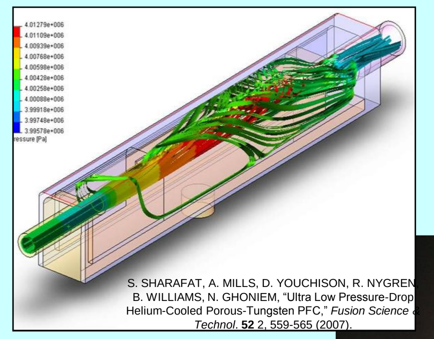
Introduction

In the 1990's Sandia performed high heat flux testing on a wide variety of moderate pressure (4 MPa) helium-cooled heat sinks under evaluation for PFC applications. Many of these contained copper and eventually refractory metal (W and Mo) porous media to enhance the effective surface area and provide improved convective cooling. The media ranged in geometry from dense sintered pellets to highly porous metallic foams. The PFC mock-ups also evolved from single channel designs to multichannel configurations.

Changes in thermal response due to flow non-uniformity appeared during electron beam testing at Sandia's Plasma Materials Test Facility. They sometimes resulted in runaway surface temperature excursions leading to surface melting. The observations occurred when applying a spatially non-uniform high heat flux over a small area or a single coolant channel in a parallel channel device for cases where the ΔT in the helium was well above 100 °C.

It was noted that until recently, no one reported computational fluid dynamics calculations predicting flow mal-distributions in multichannel devices. Present helium jet designs are not as sensitive to flow mal-distributions because unlike porous media, the jets reside in a low temperature region of the device regardless of the heat flux location and tend to have large, open exhaust ducts. This article presents some preliminary CFD analysis that does predict flow mal-distributions in porous media using the ideal gas law and lumped numerical models of the media. Our study provides valuable insight on the limited set of circumstances or boundary conditions under which instabilities or flow mal-distributions can occur in porous media.

Porous Media Experiments

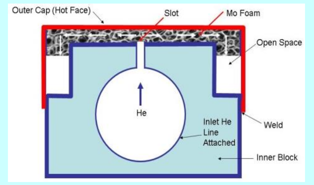


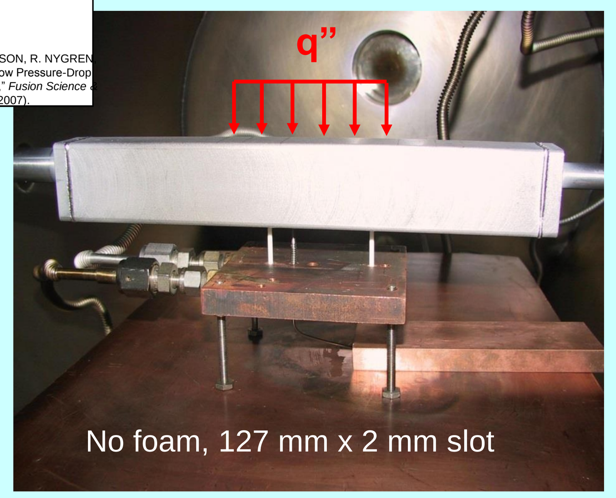
S. SHARAFAT, A. MILLS, D. YOUCHISON, R. NYGREN, B. WILLIAMS, N. GHONIEM, "Ultra Low Pressure-Drop Helium-Cooled Porous-Tungsten PFC," *Fusion Science & Technol*. **52** 2, 559-565 (2007).

Flow instabilities only occur with large ΔT in the helium (Brayton)
- look at non-uniform heating (k_{th} important)
- a) sintered tungsten pellets
- b) moly foam-filled tee tube ducts

Highly geometry dependent (channels & manifolding)

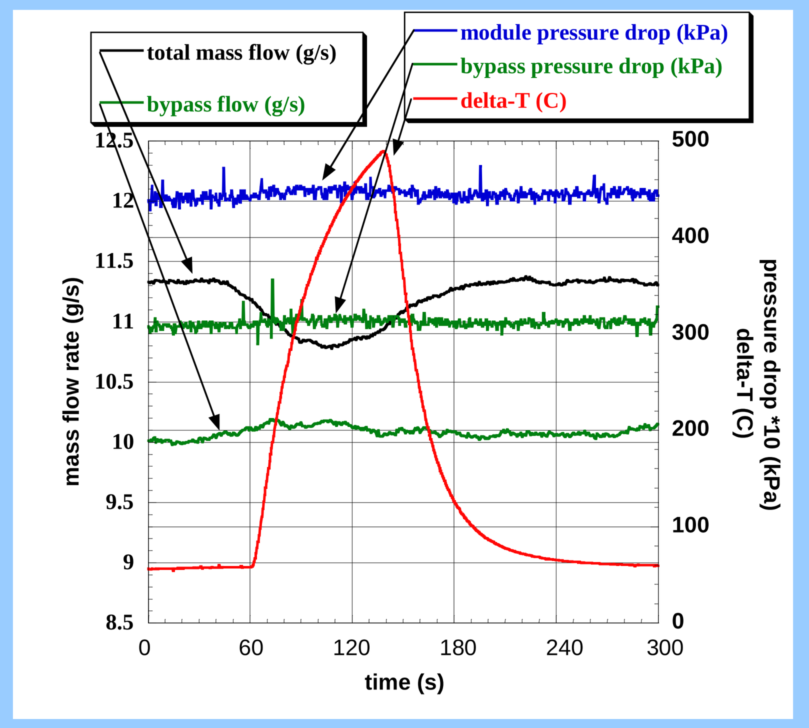
Conditions: 4 MPa, 10 g/s, q"=30 MW/m^2 foam porosity = 85%



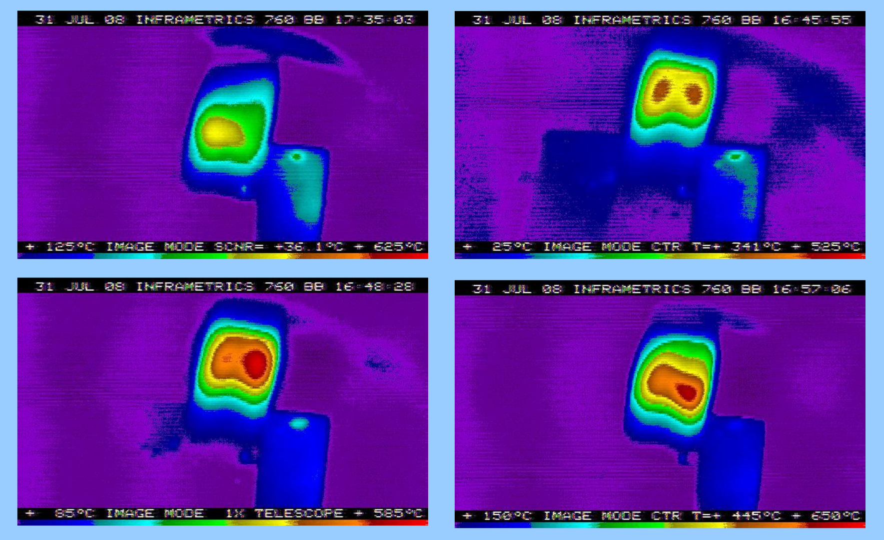


Porous Media Results

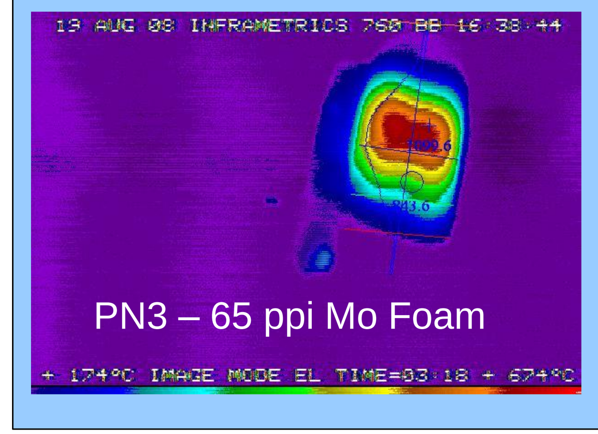
Porous media (experimental evidence)



PN1 – No Foam (open tee-tube)

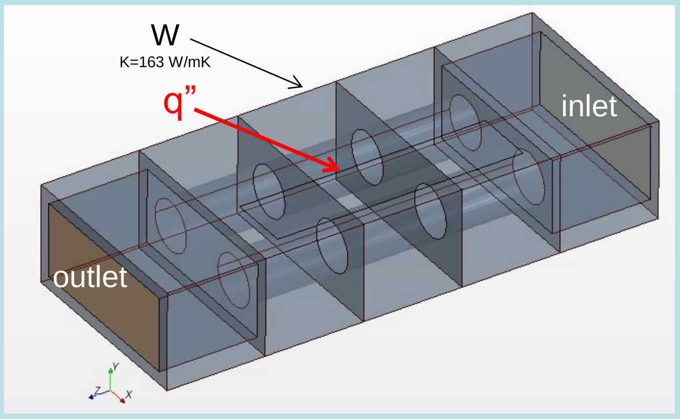


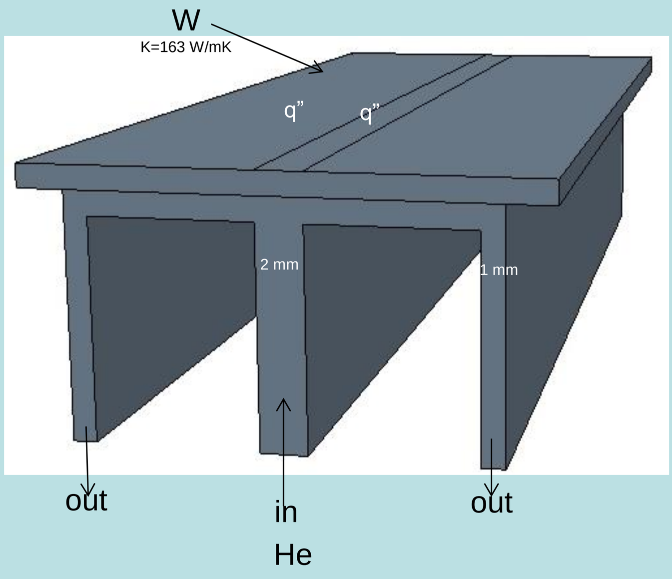
Slotted jet concepts are susceptible to flow instabilities! Slot tailoring and variable manifolding required.

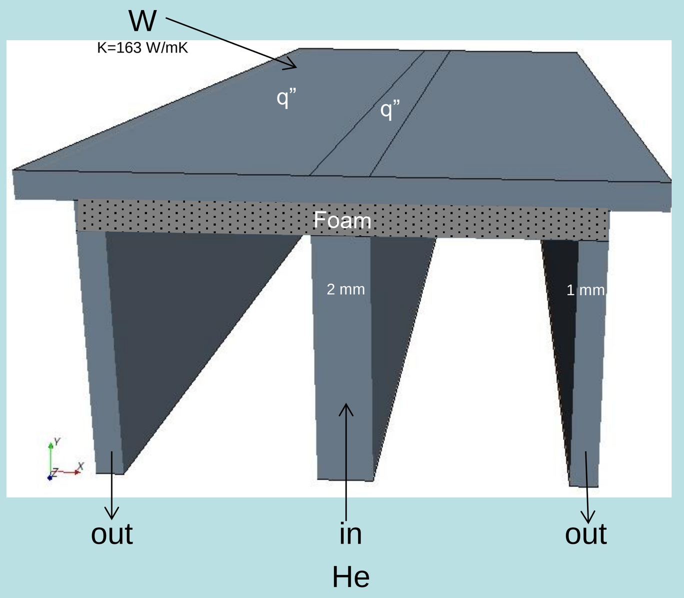


Foams or engineered pressure drops, if tolerable, can mitigate the effect.

Geometry

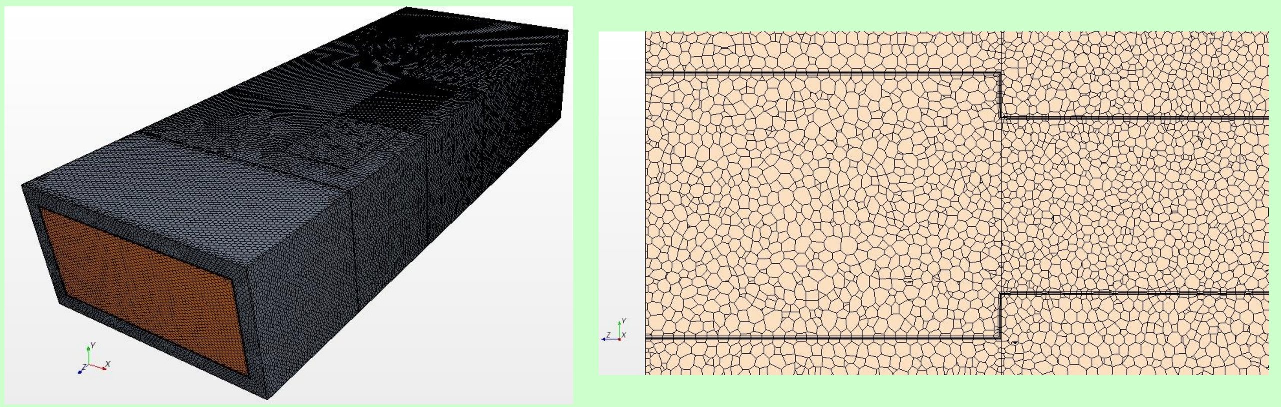




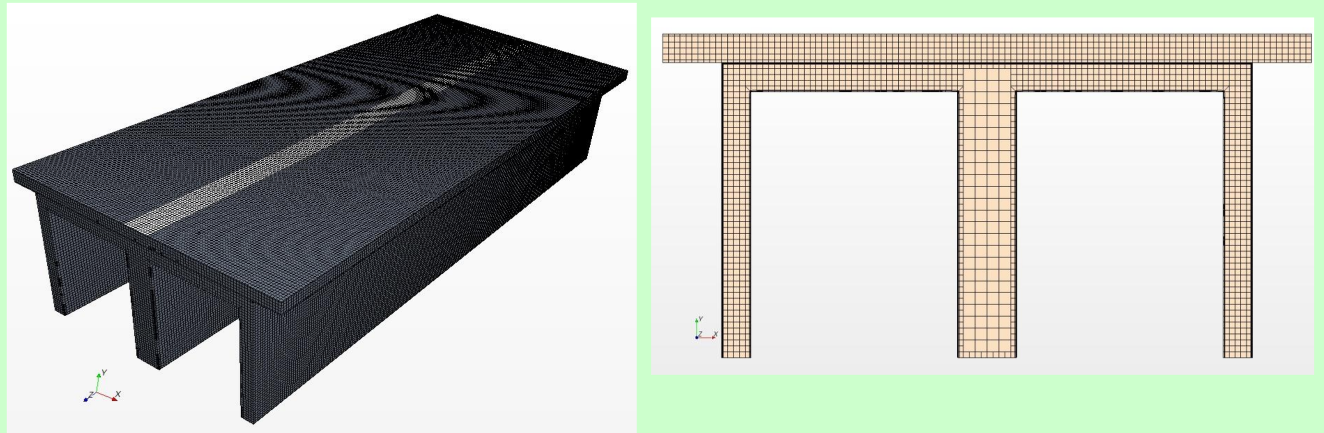


Mesh

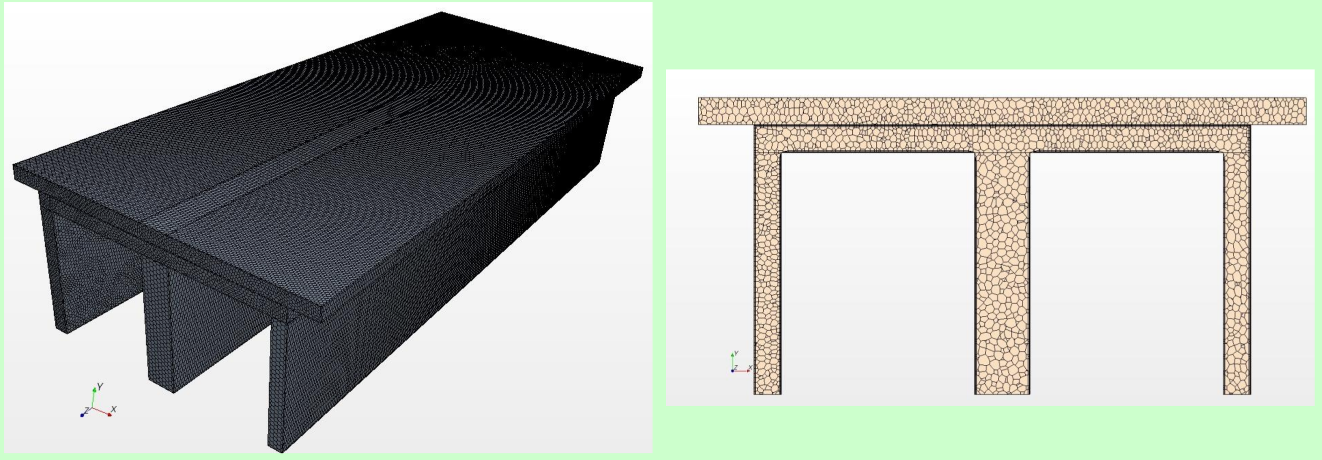
Parallel large channel model (939 k cell polyhedral mesh)



Open tee-tube model (769k cell hexahedral mesh)

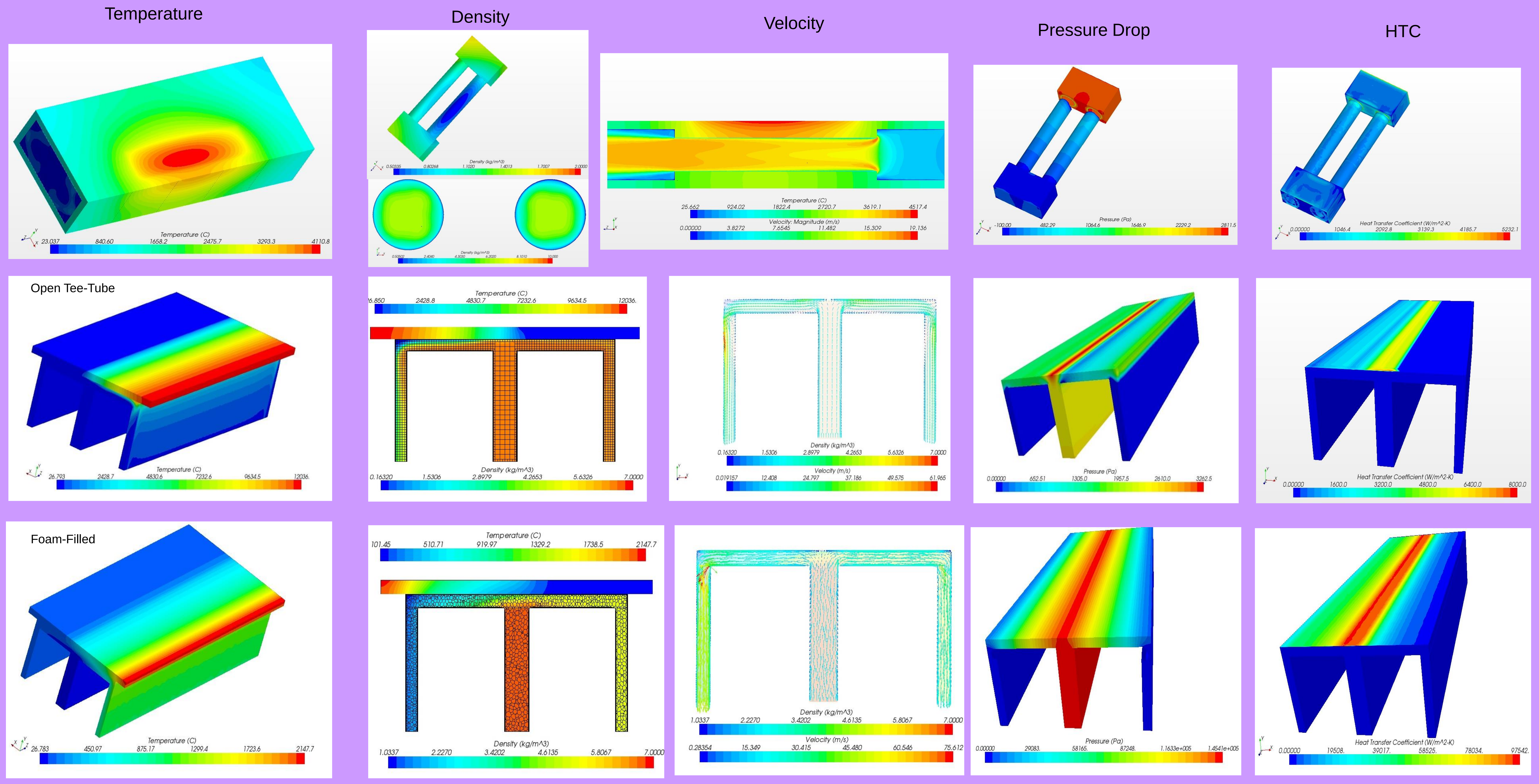


Foam-filled tee-tube model (817 k cell polyhedral mesh)



Steady state analysis using CCM+ implicit solver with 1000 iterations to convergence.
Ideal gas law used with realizable k-ε two-layer turbulence
4 MPa, 10 g/s, 300 K inlet conditions. Applied 30 MW/m² on 600 mm² heated area.

Results (30 MW/m²)



Comparison

Device	Channel Comparisons		
	Channel Number	Outlet Mass Flow (kg/s)	Outlet Temperature (C)
Round Tubes	Channel 1	4.90E-03	1.96E02
	Channel 2	5.10E-03	1.60E02
Open Tee-Tube	Channel 1	4.27E-03	2.07E02
	Channel 2	5.73E-03	3.42E01
Foam Tee-Tube	Channel 1	3.40E-03	9.05E02
	Channel 2	6.60E-03	9.87E01

```
        Mass Flow Average of Temperature on Volume Mesh
Part                                    Value (C)
--------------------------------        -------------
ColdExit                                 1.596851e+02
HotExit                                  1.955015e+02
                                        -------------
                          Total:         1.772322e+02   Δm=2%
        Mass Flow
Part                                    Value (kg/s)
--------------------------------        -------------
ColdExit                                 5.102473e-03
HotExit                                  4.900765e-03   ΔT=36 C
                                        -------------
                          Total:         1.000324e-02
```

```
Part                                    Value (kg/s)      TeeTubeW4
--------------------------------        -------------
FluidVolume: Inlet                      -1.000000e-02
FluidVolume: LeftOutlet                  4.269911e-03
FluidVolume: RightOutlet                 5.727833e-03
                                        -------------
                          Total:        -2.255729e-06   Δm=16%
Part                                    Value (C)
--------------------------------        -------------
FluidVolume: LeftOutlet                  2.006896e+02   ΔT=166 C
FluidVolume: RightOutlet                 3.416749e+01
                                        -------------
                          Total:         1.052870e+02
```

```
Part                                    Value (kg/s)      TeeTubeWFoam
--------------------------------        -------------
InletZone: Inlet                        -1.000000e-02
OutletLeft: OutletLeft 2                 3.400781e-03
OutletRight: OutletRight 2               6.599184e-03
                                        -------------
                          Total:        -3.492989e-08   Δm=32%
 Part                                    Value (C)
 --------------------------------        -------------
 OutletLeft: OutletLeft 2                 9.053768e+02   ΔT=806 C
 OutletRight: OutletRight 2               9.872908e+01
                                         -------------
                          Total:         3.730533e+02
```

Large open-channel devices showed very minor effects due to spatially non-uniform heating. In contrast, the narrow channel devices showed significant flow redistribution scaling with the ΔT of the helium. Although temporal variation was minimized by adding high density foam in narrow channels, constant, spatially non-uniform heating was shown to produce even greater reductions in the hot channel mass flow compared to an open narrow channel.

-- Conclusions --

These numerical experiments showed mal-distributions of helium mass flow are more prevalent in refractory metal devices with small channel sizes under significant heat load producing helium ΔTs of several hundred degrees. Large channel, high thermal conductivity devices are not as likely to develop flow distribution problems. Also, high pressure drop, dense porous media devices are more resilient to temporal instabilities than higher porosity devices at the cost of more pumping power.

Acknowledgments: The authors wish to thank Tom Lutz, Jimmie McDonald and Fred Bauer for obtaining the experimental high heat flux data. We also wish to thank Brian Williams of Ultramet, Inc. and John Rosenfeld of Thermacore, Inc. for providing the porous media test articles.

Sandia National Laboratories

Sandia is a multiprogram laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation,
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

National Nuclear Security Administration