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Flow Instabilities in Non-Uniformly Heated Helium Jet Arrays Used for Divertor PFCs

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Abstract: Due to a lack of prototypical experimental data, little is known about the off-normal behavior of recently proposed divertor jet cooling concepts. Here we describe a computational fluid dynamics (CFD) study on two jet array designs to investigate their susceptibility to parallel flow instabilities induced by non-uniform heating and large increases in the helium outlet temperature. The study compared a single 25-jet helium-cooled modular divertor (HEMJ) thimble and a micro-jet array with 116 jets. Both have tungsten armor and manifold and a mass flow rate of 10 g/s at a 600 ºC inlet temperature. We investigated flow perturbations caused by a 30 MW/m^2 off-normal heat flux applied over a 25 mm^2 area in addition to the nominal 5 MW/m^2 applied over a 75 mm^2 portion of the face. The micro-jet array exhibited lower temperatures and a more uniform surface temperature distribution than the HEMJ thimble.

For the 30 MW/m^2 case, the micro-jet array absorbed 750 W in the helium with a maximum armor surface temperature of 1057 ºC and a fluid/solid interface temperature of 912 ºC. The HEMJ absorbed 750 W with a maximum armor surface temperature of 1411 ºC and a fluid/solid interface temperature of 844 ºC. A single HEMJ finger uses 5-mm-thick tungsten armor compared to the 1 mm armor on the micro-jets. The extra thickness spreads the heat load making the HEMJ resistant to flow instabilities. The maximum surface temperature varies with the thickness of the tungsten wall. However, the ratio of maximum to average temperature and variations in the local heat transfer coefficient were lower for the micro-jet array compared to the HEMJ device.

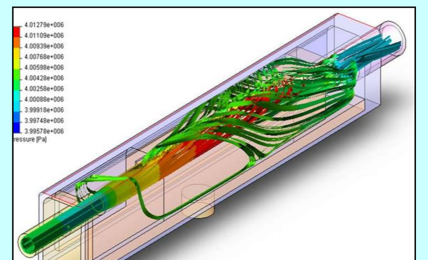
Introduction

Jet impingement cooling is under development for the divertor of high power density toroidal fusion reactors. Questions concerning the susceptibility of the jets to flow instabilities during off-normal transients and localized heating remain.

High heat flux testing of actively cooled porous media heatsinks revealed that such flow instabilities are easy to produce during non-uniform one-sided heating. Recently, this behavior was demonstrated numerically using computational fluid dynamics in porous media as shown below.

To date, HHF testing has not revealed the presence of flow instabilities for the 9-finger HEMJ module. Other promising configurations such as the micro-jet array used in electronics cooling have yet to be tested in the lab at high heat flux. Therefore, we undertook a CFD study to evaluate the susceptibilty of jet arrays to parallel flow maldistributions.

Porous Media



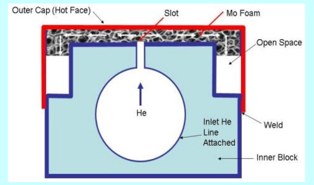
S. SHARAFAT, A. MILLS, D. YOUCHISON, R. NYGREN, B. WILLIAMS, N. GHONIEM, "Ultra Low Pressure-Drop Helium-Cooled Porous-Tungsten PFC," *Fusion Science & Technol*. **52** 2, 559-565 (2007).

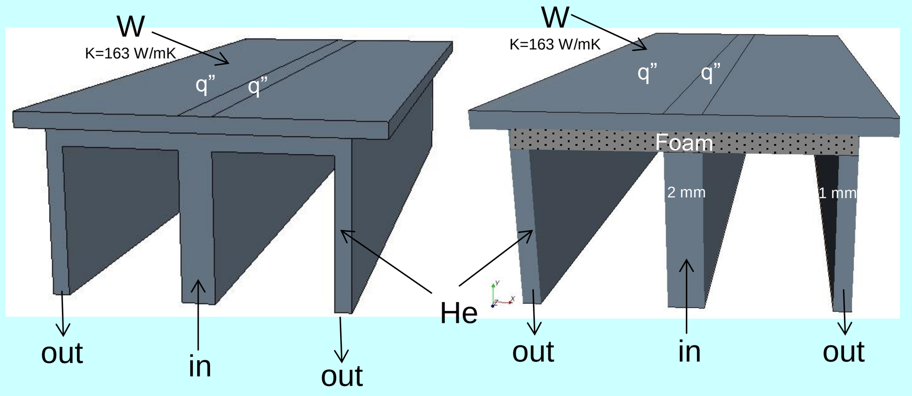
Flow instabilities only occur with large ΔT in the helium (Brayton)

- ➢ look at non-uniform heating (k_{th} important)
- a) smooth open tee tube rectangular ducts
- b) foam-filled tee tube ducts

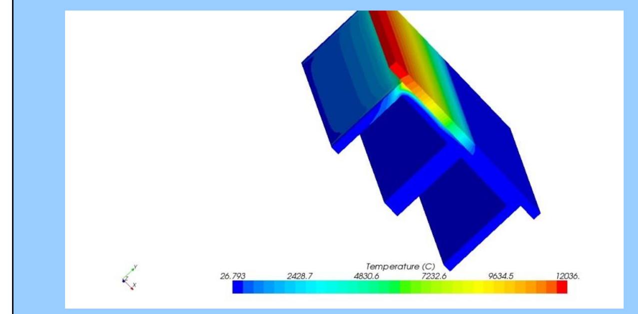
Highly geometry dependent (channels & manifolding)

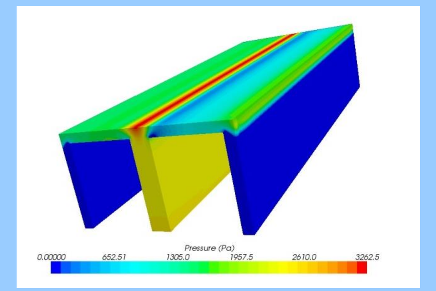
Conditions: 4 MPa, 10 g/s, q"=30 MW/m^2 foam porosity = 70%

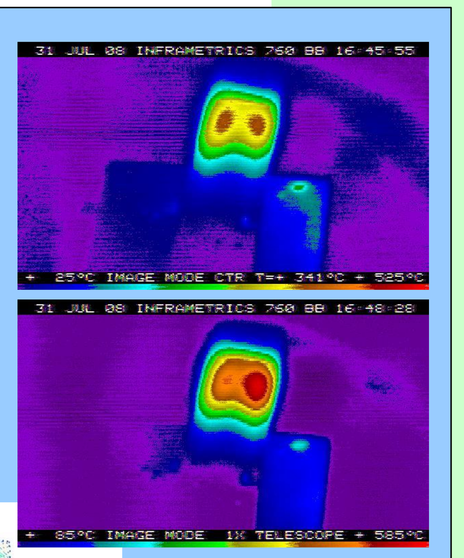


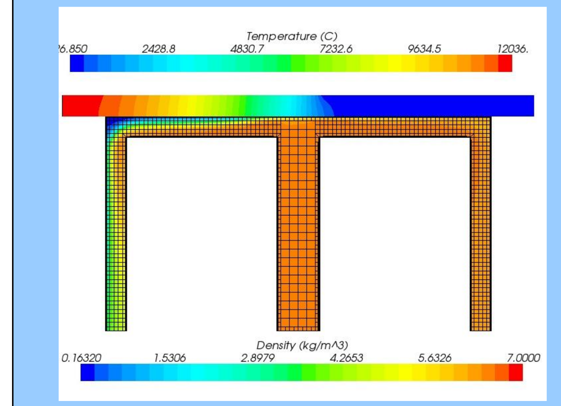


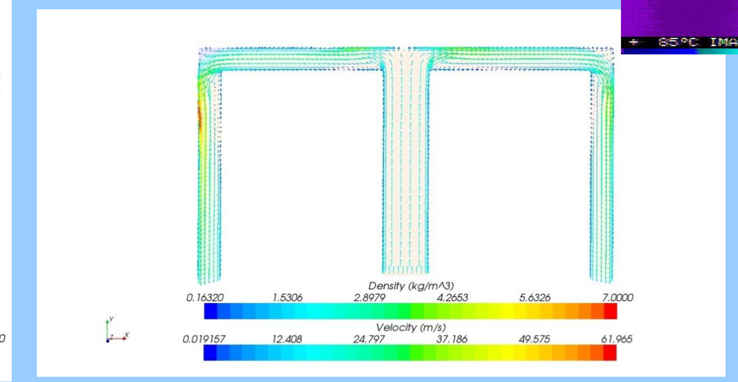
Porous Media Results





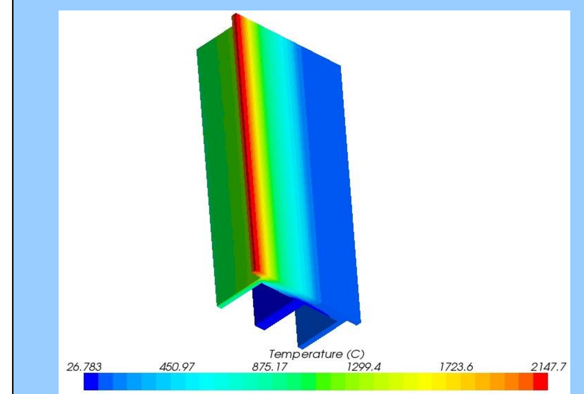


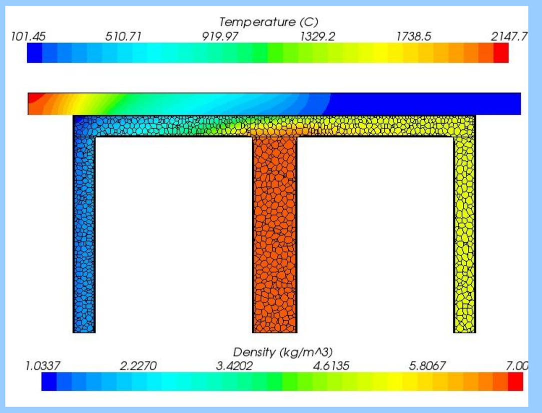


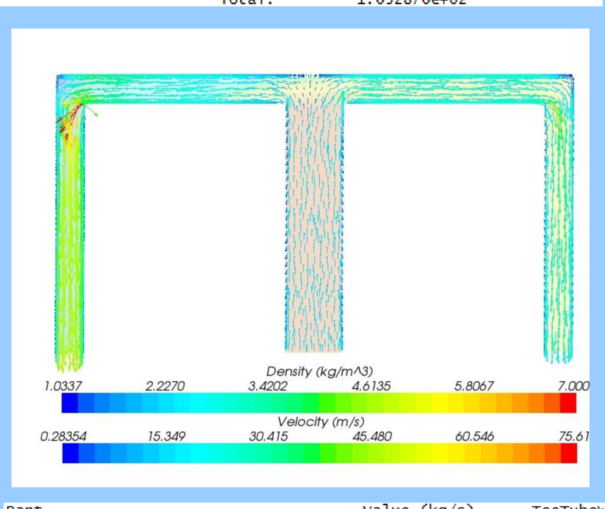


Part	Value (kg/s)	TeeTubeW4
FluidVolume: Inlet	-1.000000e-02	
FluidVolume: LeftOutlet	4.269911e-03	
FluidVolume: RightOutlet	5.727833e-03	
Total:	-2.255729e-06	

Part	Value (C)
FluidVolume: LeftOutlet	2.006896e+02
FluidVolume: RightOutlet	3.416749e+01
Total:	1.052870e+02





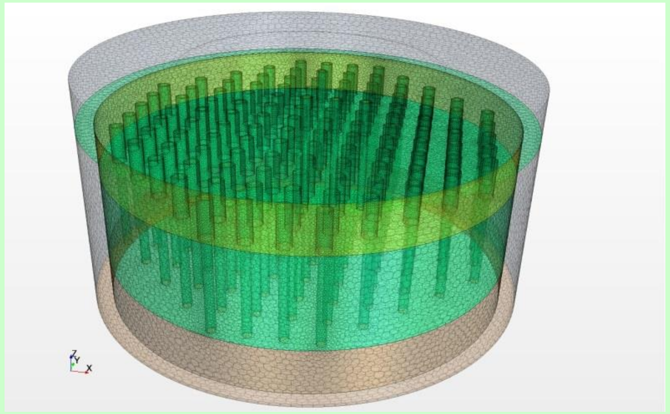


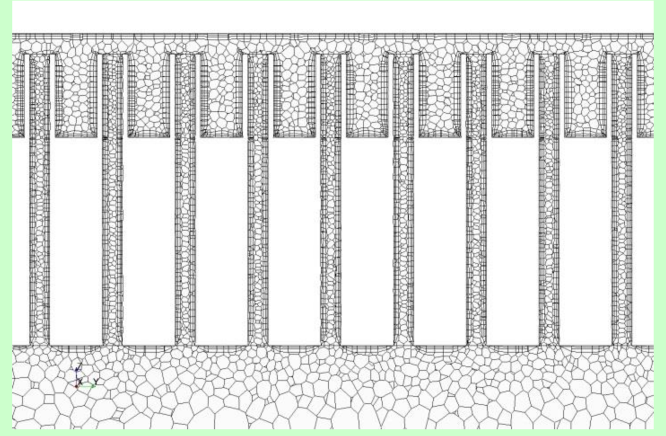
Part	Value (kg/s)	TeeTubeWFoam
InletZone: Inlet	-1.000000e-02	
OutletLeft: OutletLeft 2	3.400781e-03	
OutletRight: OutletRight 2	6.599184e-03	
Total:	-3.492989e-08	

Part	Value (C)
OutletLeft: OutletLeft 2	9.053768e+02
OutletRight: OutletRight 2	9.872908e+01
Total:	3.730533e+02

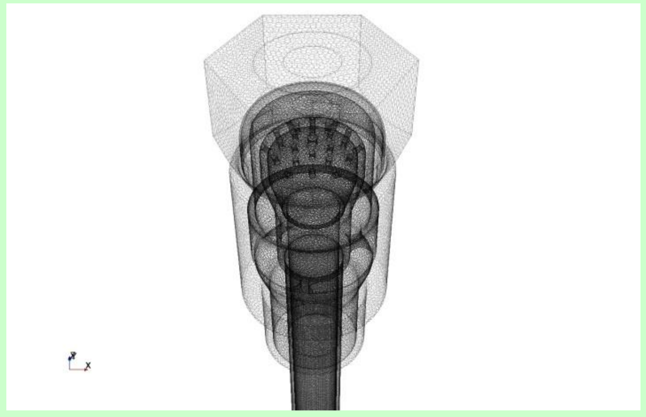
Mesh

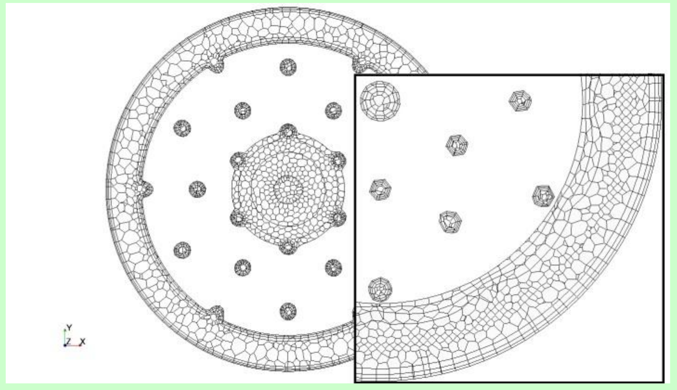
Micro-jet array (116 jets)



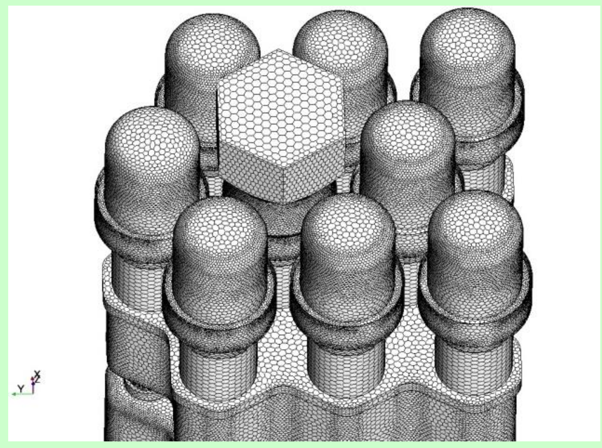


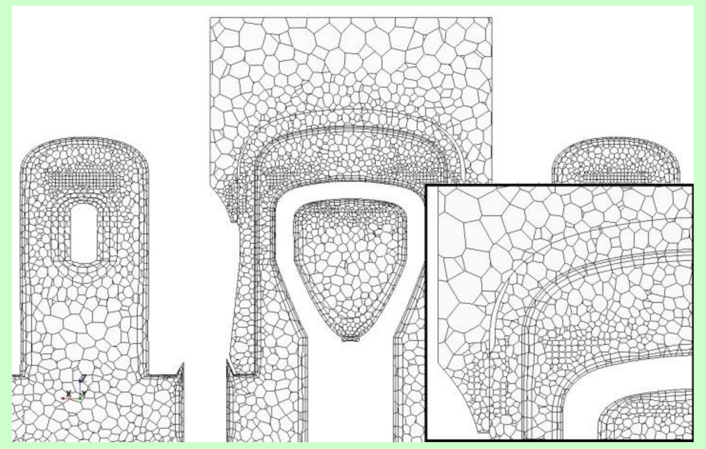
Single HEMJ module (25 jets)



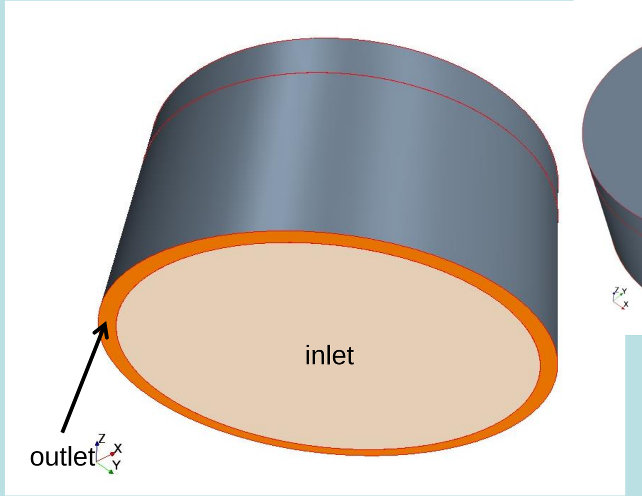


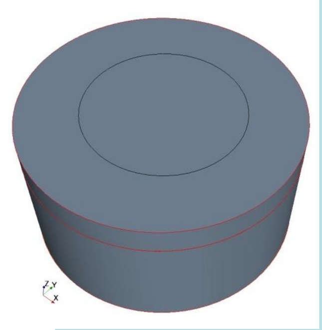
Nine-finger HEMJ assembly (225 jets)

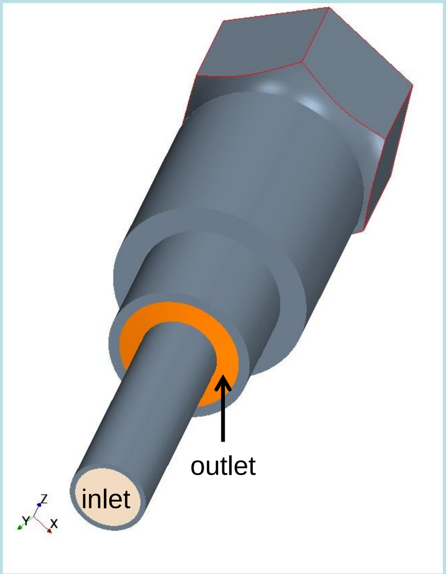


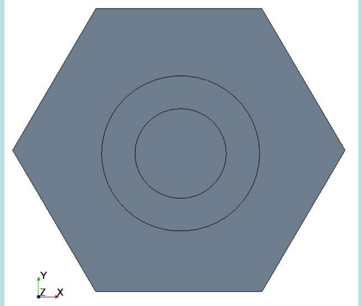


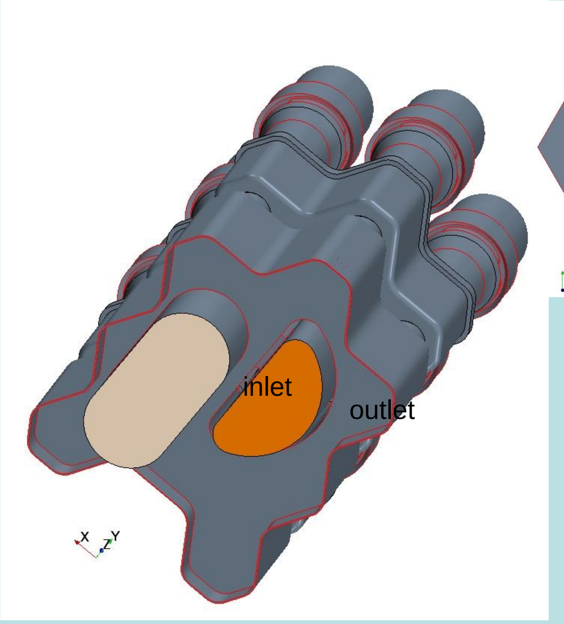
Geometry

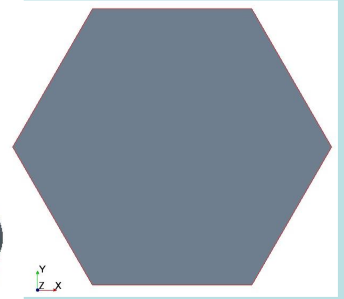








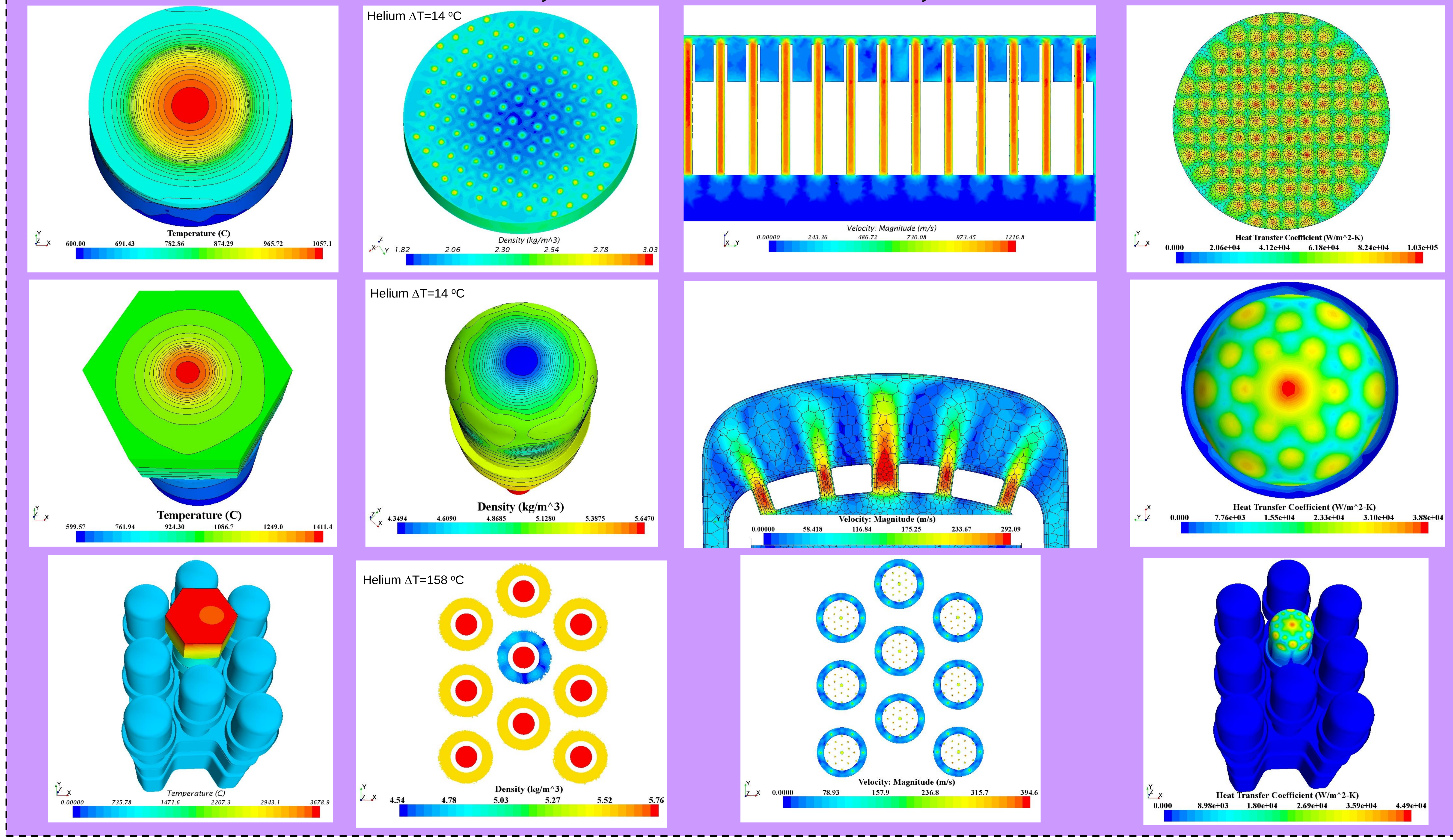




Transient analysis using CCM+ implicit steady state solver with 1000 iterations to convergence.
Ideal gas law used with realizable k-ε turbulence
4 & 10 MPa, 10 g/s, 600 °C inlet conditions. Applied 5 MW/m² and 30 MW/m² on 75 mm² and 25 mm² heated areas, respectively.

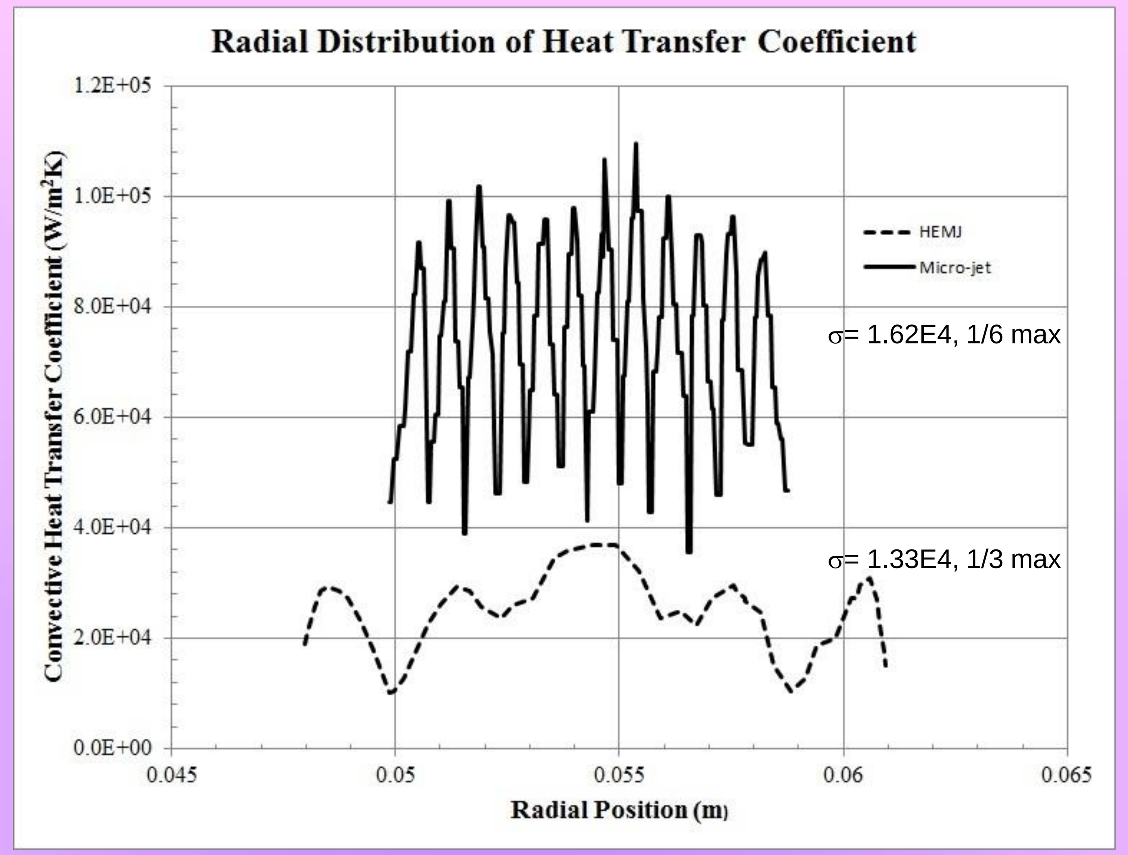
Results (30 MW/m²)

Temperature | Density | Velocity | HTC



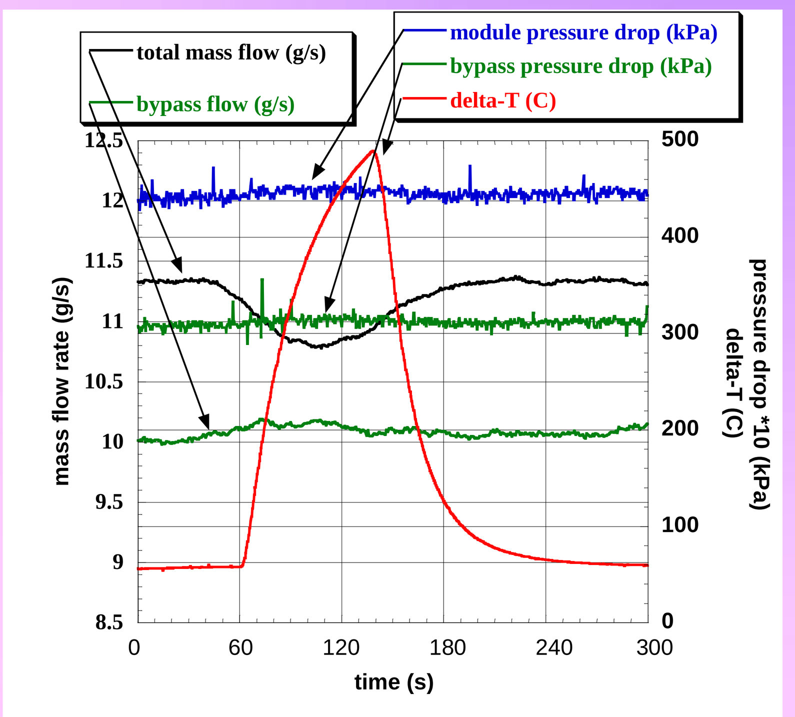
Comparison

Jet Arrays



Both the HEMJ and the micro-jet array performed well under spatially non-uniform heating. No evidence of flow instabilities appeared in the simulations. Although the density and velocity distributions in the exit plenum changed significantly due to the heating, no appreciable difference in the mass flow distribution resulted under the heated wall or through the jet array.

Porous media (experimental evidence)



Individual mass flow rates, monitored for each jet revealed no significant difference in mass flow rates even though the densities and velocities were significantly different under the heated areas. For the 9-finger assembly the velocity was 7% higher, while the density was 12% lower on the heated finger for the most severe case. There was little variation in total pressure drop between fingers.

-- Conclusions --

The porous media appears to have an increase in dynamic pressure drop as the velocity increases due to gas expansion. The incoming flow is affected due to the higher back pressure on the exhaust side created by helium ΔTs of several hundred degrees because of collisions between the faster moving hot helium molecules and the media itself. The reduced volume available to accommodate the gas expansion exacerbates the effect. This means the amount of porous media and the length of flow path after the heat addition must be minimized to improve performance. This does not affect the jet arrays when designed with a large, open exhaust duct or operating at lower ΔTs.

The conclusion above is valid when the exhaust plenum has significantly more flow area and volume than the sum of the jets. The cold jets dominate the pressure drop in the jet arrays. Therefore, if provided with adequate expansion volume in the exhaust plenum, heating of the gas will have little effect on changing the pressure distribution between jets or even between individual array modules.

The analyses reported here verified that smaller micro-jets can produce a more uniform distribution of the heat transfer coefficient at the heated wall and minimize large temperature gradients that lead to higher thermal stresses. The micro-jets must use a nozzle structure to minimize interference, and the overlap of deleterious turbulence patterns between neighboring jets that can lead to larger, non-uniform stagnation areas. Thicker armor also helps to spread the heat load at the expense of higher surface temperatures.

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NNSA National Nuclear Security Administration