Recent Analyses and Results for Helium-Cooled Divertor Module Experiments

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Objective/Motivation

- **Primary objective:**
  - To evaluate and experimentally-validate the thermal performance of leading Gas-Cooled Divertor Module Designs
- **Motivation:**
  - Leading gas-cooled divertor module designs rely on jet impingement cooling to achieve the desired levels of performance
  - Heat fluxes up to 10 MW/m^2 can be accommodated
  - Performance is “robust” with respect to manufacturing tolerances and variations in flow distribution
  - Extremely high heat transfer coefficients (~ 50 $kW/m^2.K$) predicted by commercial CFD codes used for the design
  - It was deemed necessary to experimentally validate the numerical results in light of the extremely high heat transfer coefficients

Approach/Outcomes

- **Approach:**
  - Design test modules that closely match the geometry of the proposed leading divertor module designs
  - Conduct experiments at conditions matching/spanning expected non-dimensional parameter range for prototypical operating conditions
  - Measure detailed temperature distributions
  - Compare experimental data to performance predicted by commercial CFD software for test geometry/conditions
- **Outcomes:**
  - Enhanced confidence in predicted performance by CFD codes at prototypical and off-normal operating conditions
  - Validated CFD codes can be confidently used to optimize/modify design
  - Performance sensitivity to changes in geometry and/or operating conditions can be used to define/establish manufacturing tolerances

Scope

All Leading Gas-Cooled Divertor Designs

- FZK Helium-Cooled Multi-Jet (HEMJ), Norajitra, et al. (2005)
- ARIES-CS T-Tube Design, Ihli, et al. (2006)
- ARIES-TNS Plate Design, Malang, Wang, et al. (2008)
  – Metal-Foam-Enhanced Plate Design, Sharafat, et al. (2007)
  – Pin (Fin)-Enhanced Plate Design -- in Progress

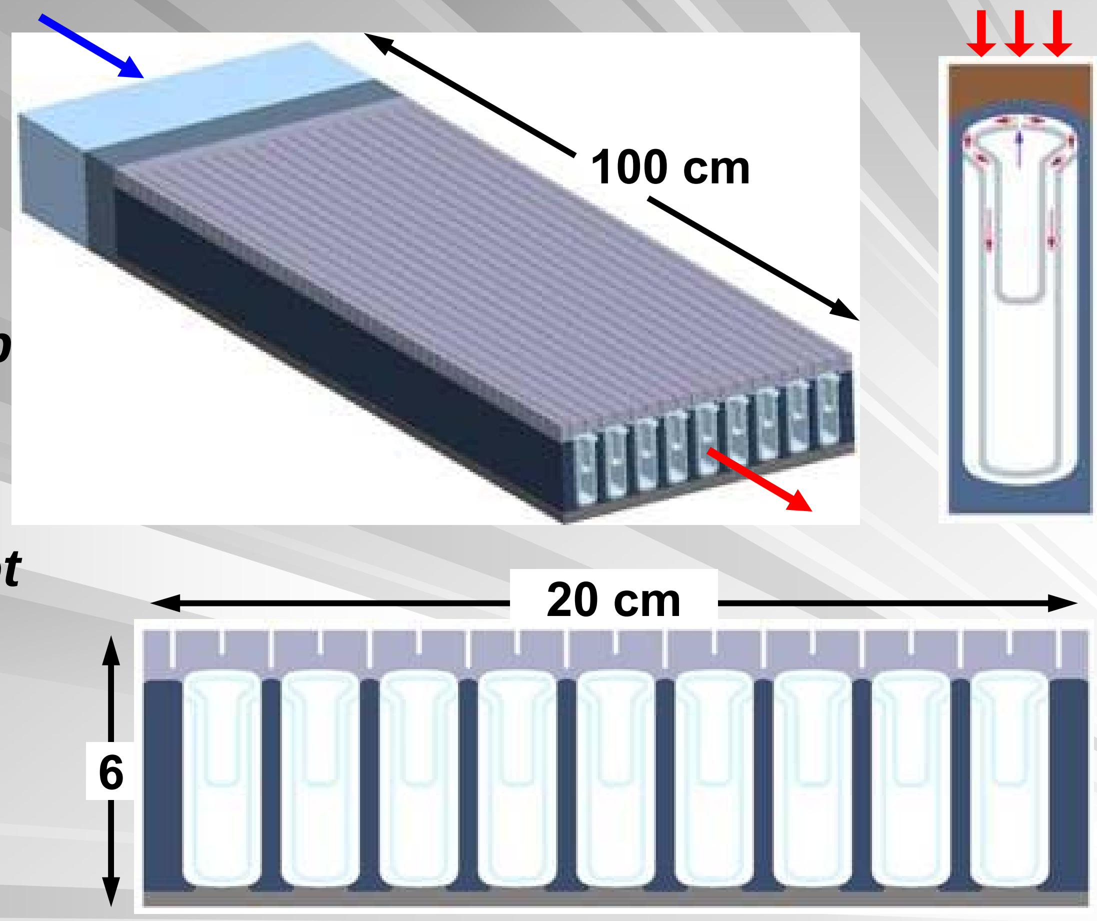
Case Study

Plate-Type Divertor Design

Plate Type Divertor Design

Large modules

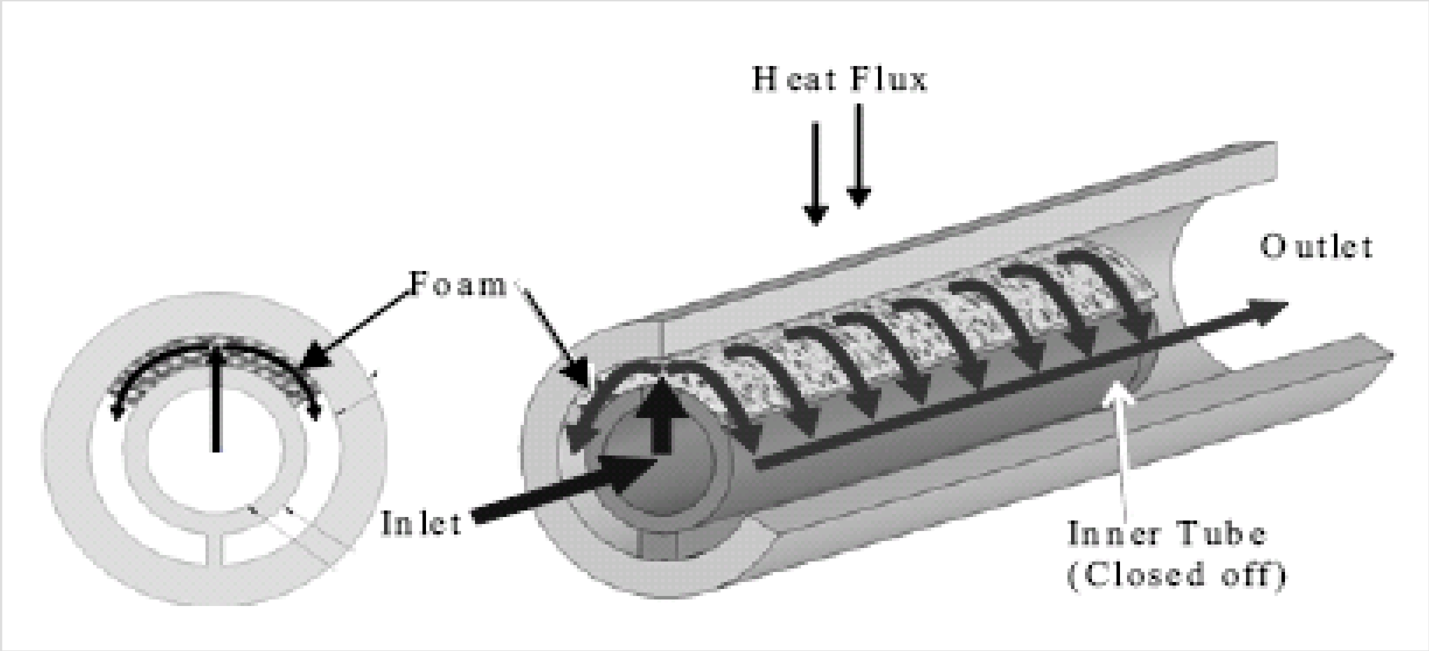
- ***Only ~750 needed for ARIES-AT***
- ***Handles heat fluxes up to 10 MW/m^2***
- ***High heat transfer coefficient: HTC w/slot jet impingement 3.9×10^4 $W/(m^2 \cdot K)$***
- ***Does not exceed temperature, stress limits***



(Malang, Wang, et al., 2008)

SOFIT- **S**hort Fl**o**w-Path **F**oam-**I**n-**T**ube

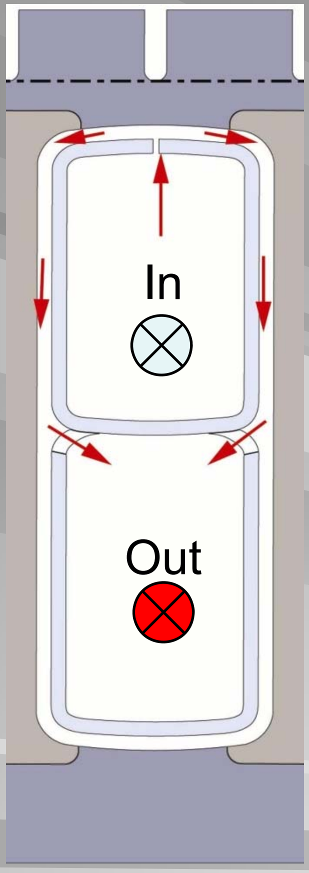
- Open-cell Metallic Foam - promotes turbulent mixing and increases cooling area
- Foam is selectively located to minimize pressure drop
- Modular Design
- Can accommodate heat fluxes up to 10 MW/m^2 (predicted)



(Sharafat et al., 2007)

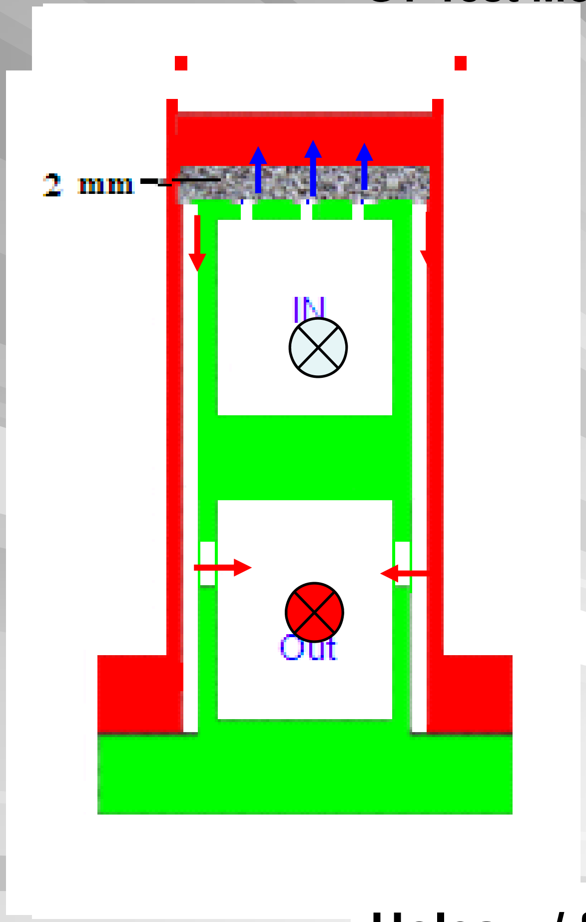
Test Module Design / Variations

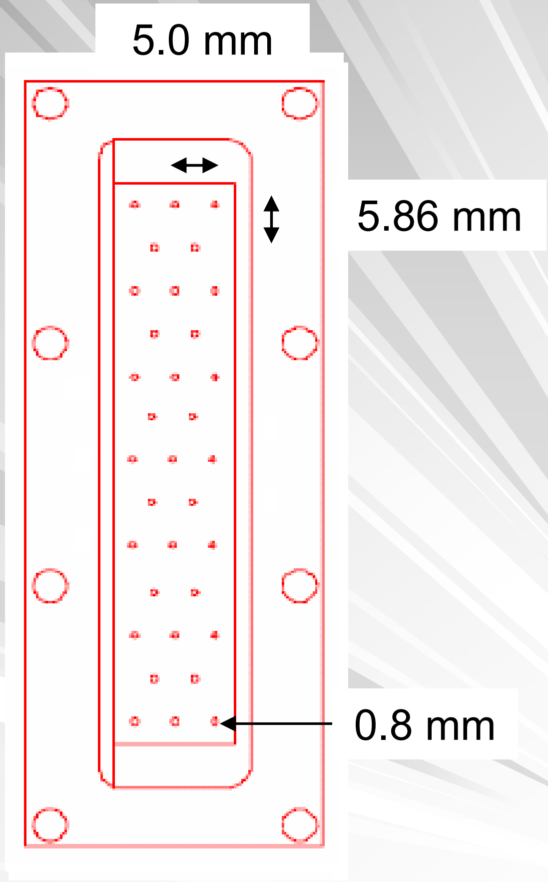
ARIES Plate Design



(Malang 2007)

GT Test Modules

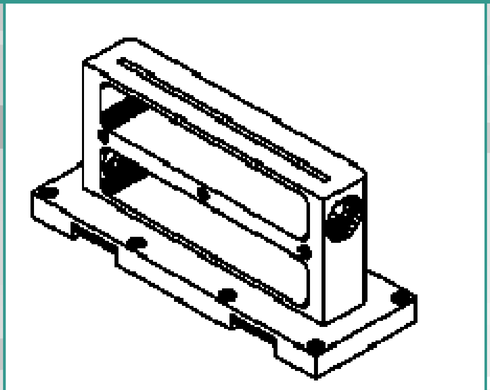




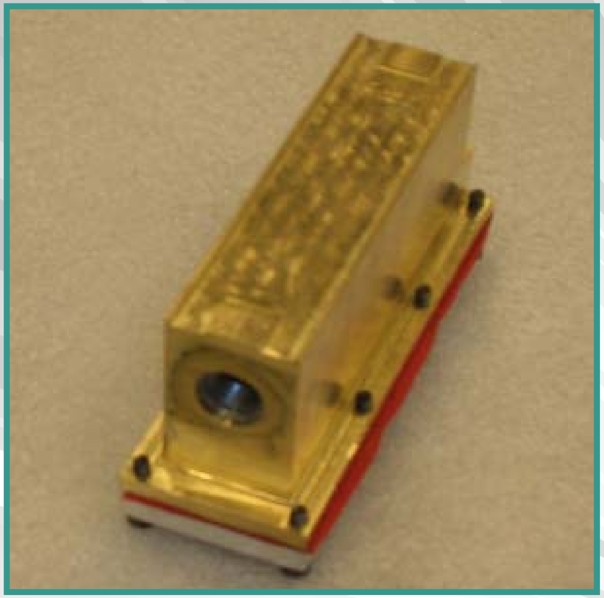
Holes w/ foam

Test Modules

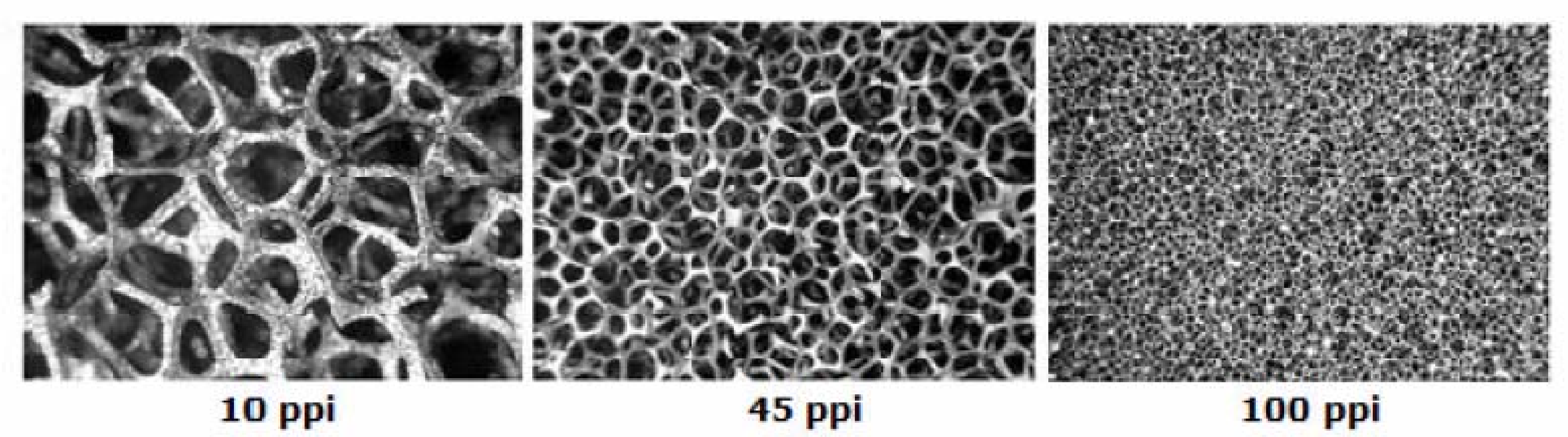
Al Inner Cartridge



Brass Outer Shell



Metal Refractory Open-Cell Foam



(Ultramet, 2008)

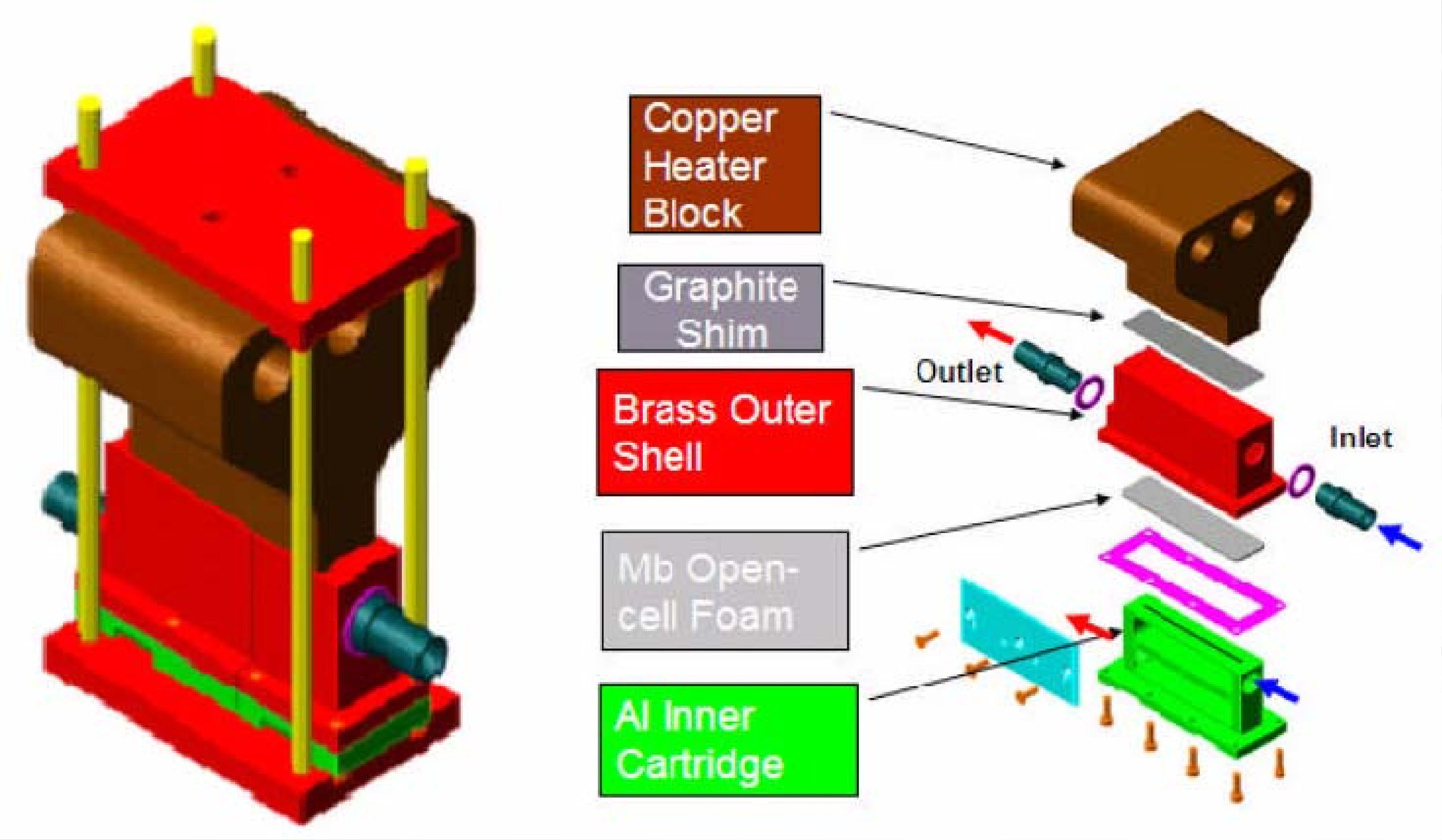
Advantages

- Customizable pore size and porosity
  - to optimize HTC/pressure drop
- High Surface Area
- Low Pressure Drop

GT specifics

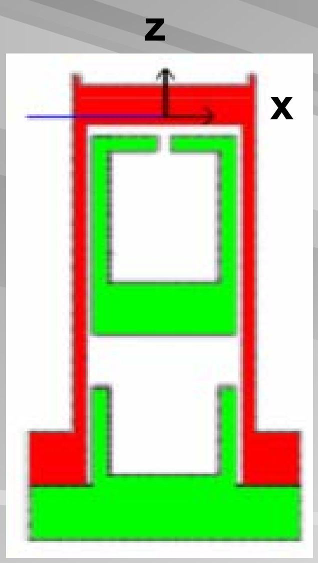
•Molybdenum
•2 mm thick
•45 ppi (70% porosity)
•65 ppi (88% porosity)
•100 ppi (86% porosity)

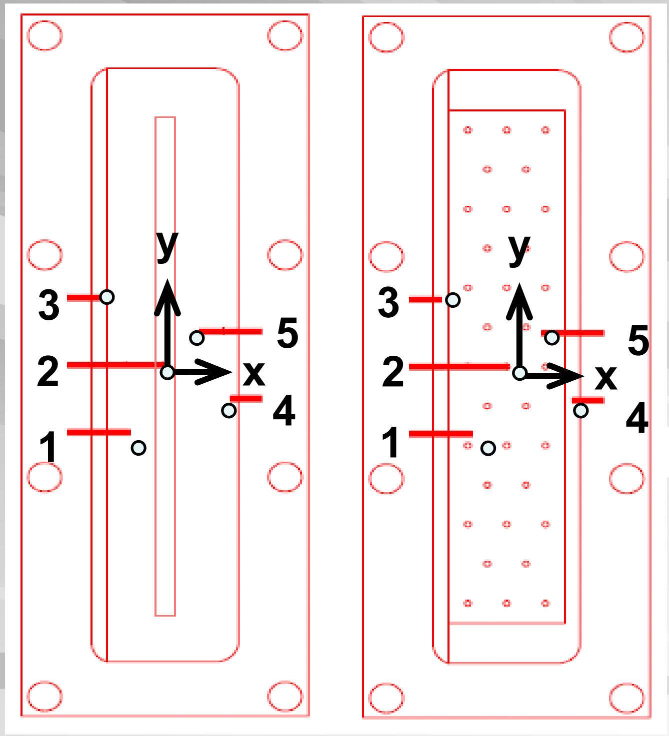
Test Module Assembly



Cooled Surface Temperature Measurement

- Five TCs (Ø 0.61 mm) embedded just inside cooled brass surface to measure local temperatures
- TC 2 at origin

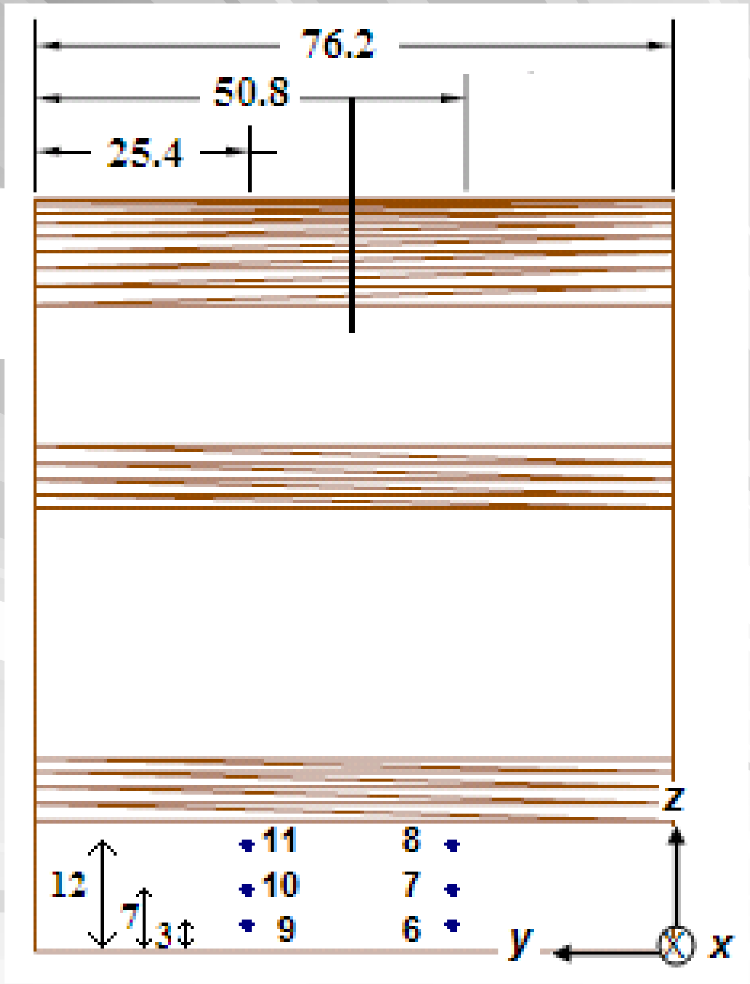




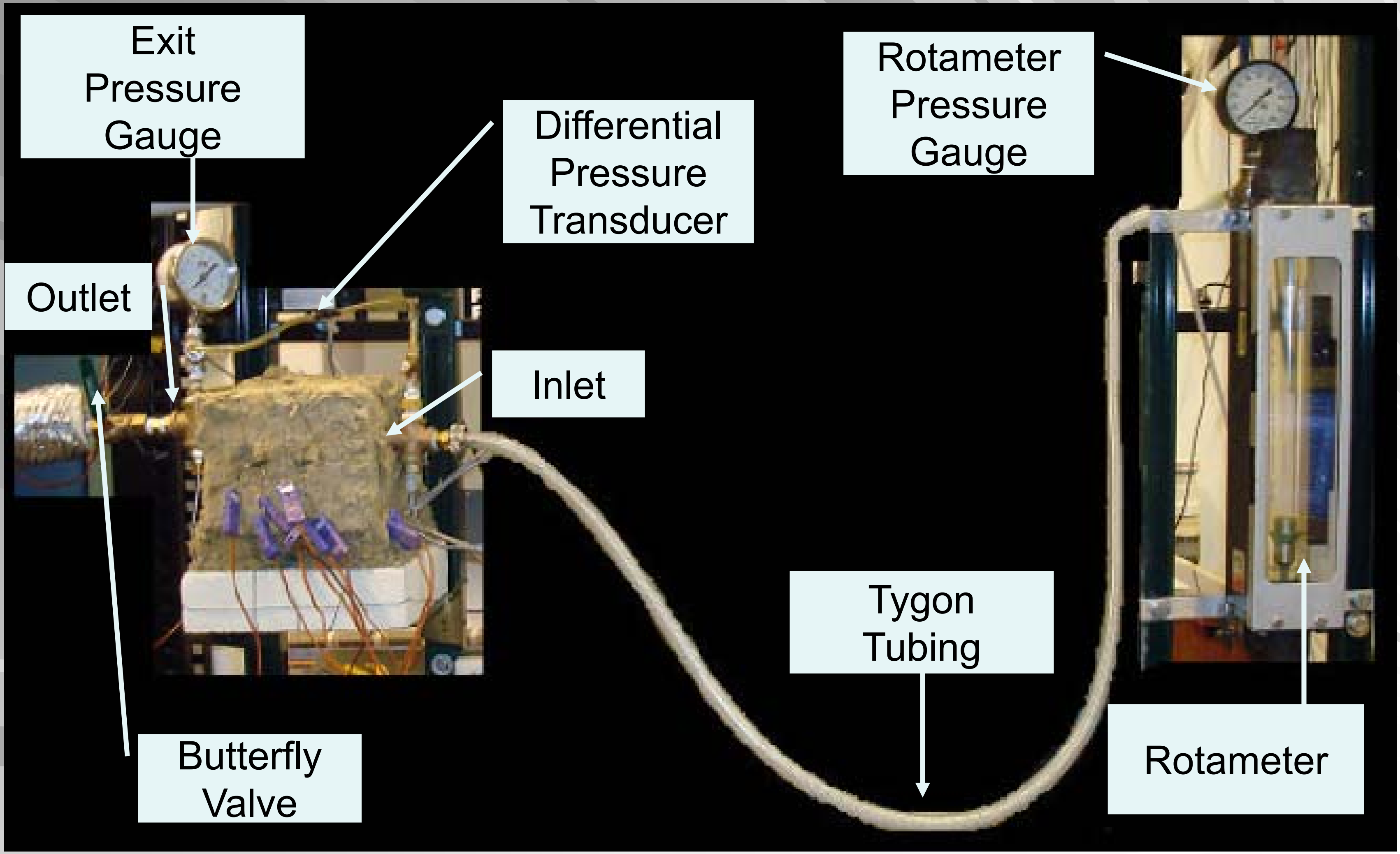
TC	x [mm]	y [mm]
1	-4.5	-10
2	0	0
3	-8.5	10
4	8.5	-5
5	4.5	5

Heat Flux Measurement

- Six TCs are embedded in the "neck" of the concentrator to measure the incident heat flux.
- Two TCs are embedded in the top of the copper heater block to monitor the peak temperature of the copper.



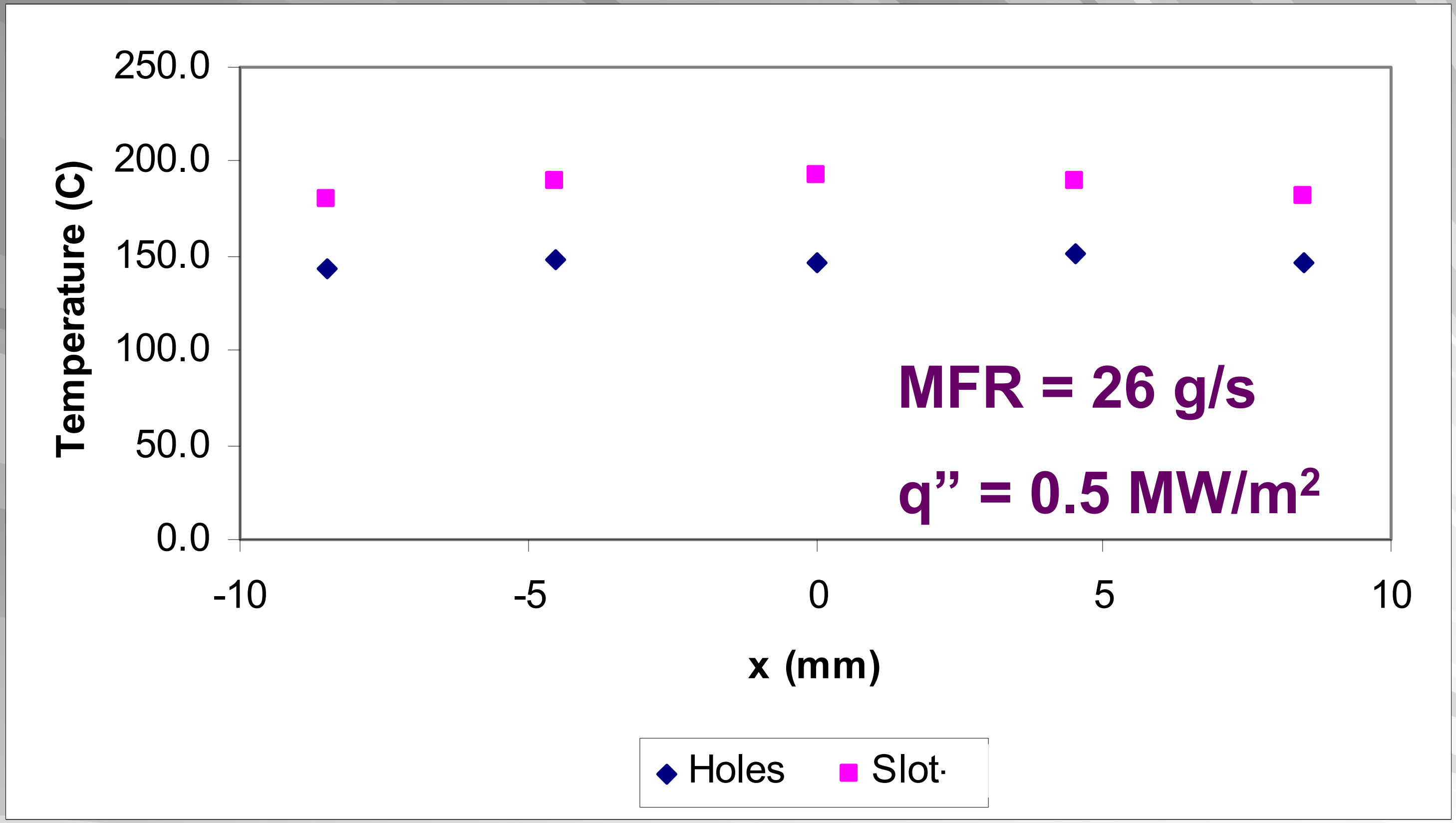
GT Air Flow Loop



Thermal Hydraulic Parameters

Parameter	Air (Holes)	Air (Slot)	Helium (ARIES)
Operating Pressure [MPa]	0.1 – 0.5	0.4 – 0.5	10
Mass Flow Rate [g/(s·m)]	61 – 344	118 – 528	702
Inlet Temp. [°C]	23	23	600
Hydraulic Diameter D_h [mm]	0.8	4	1
Re ($\times 10^4$)	1.1 – 6.8	1.3 – 6.8	3.3
Pr	0.73	0.73	0.66

Slot vs. Holes Jet Geometry

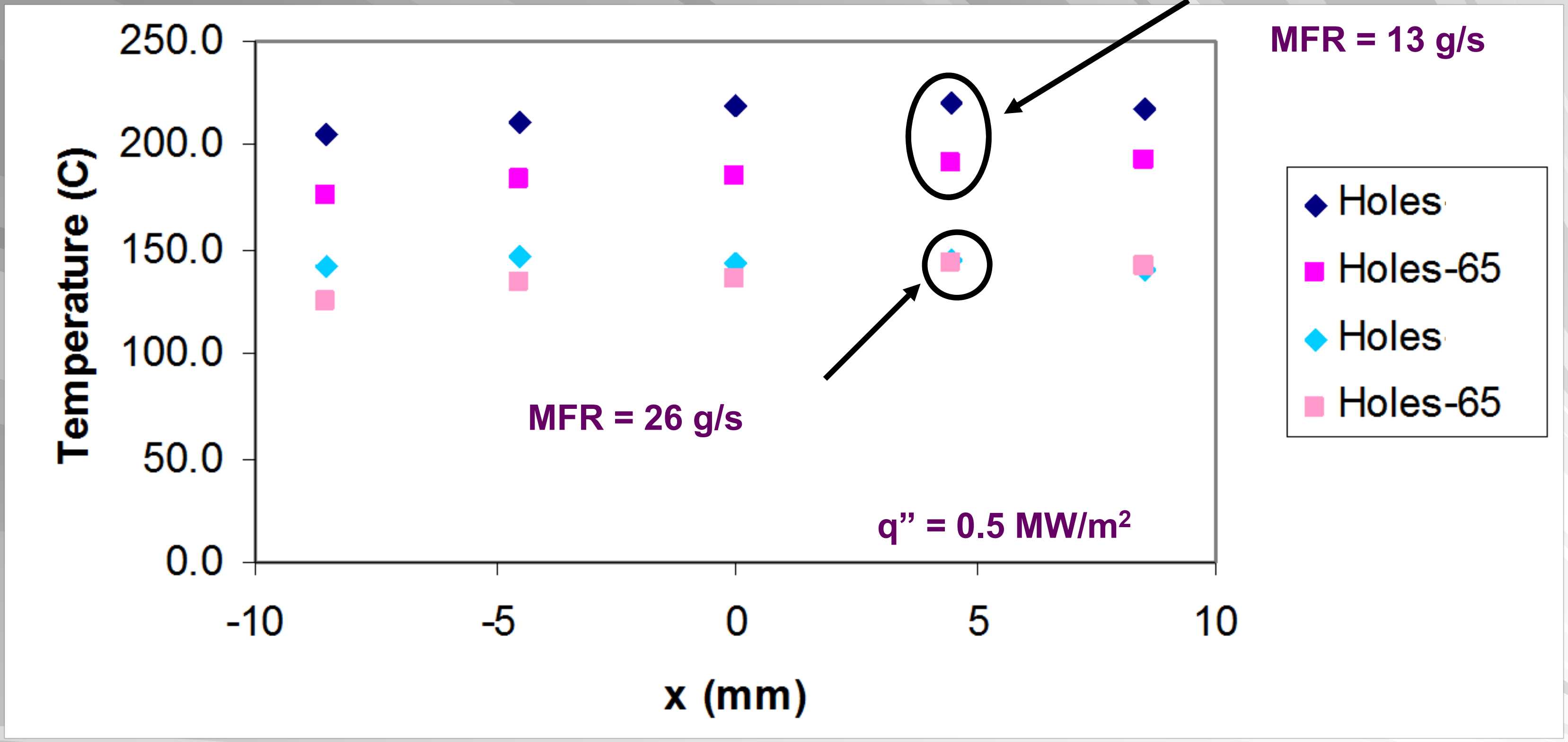


(Re_h = 66,000; Re_{sl} = 36,000)

$h_{avg\_holes} = 1.33 * h_{avg\_slot}$

$\triangle P'_{holes} = 1.96 * \triangle P'_{slot}$

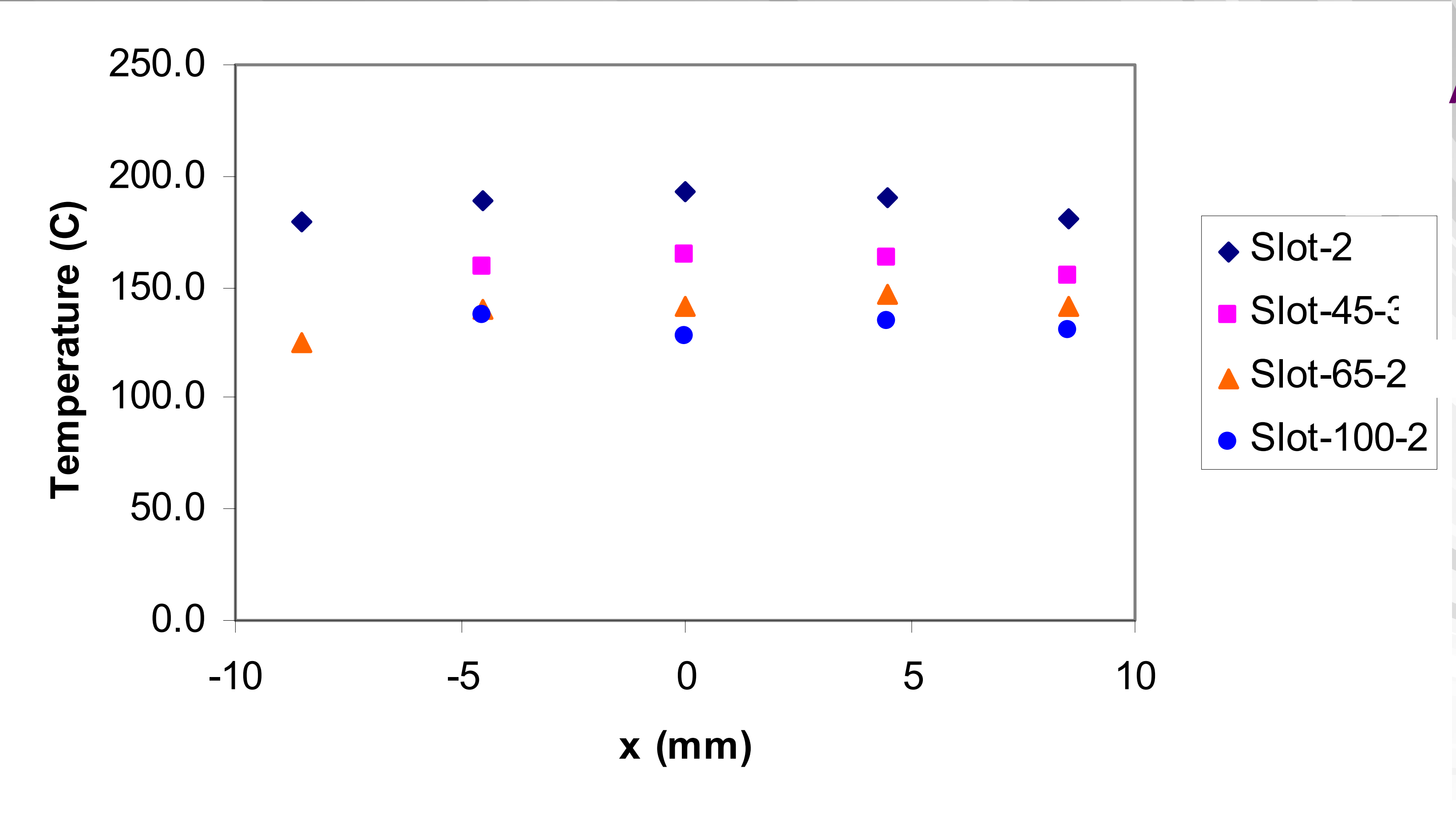
Effect of 65 ppi Metal Foam Insert for the *Holes* Test Configuration



At MFR = 13 g/s, the avg. HTC enhancement with foam is 19%.

At MFR = 26 g/s, the avg. HTC enhancement with foam is only 7%

Effect of 45, 65, and 100 ppi Metal Foam Insert for the Slot Test Configuration



Avg. HTC Increase

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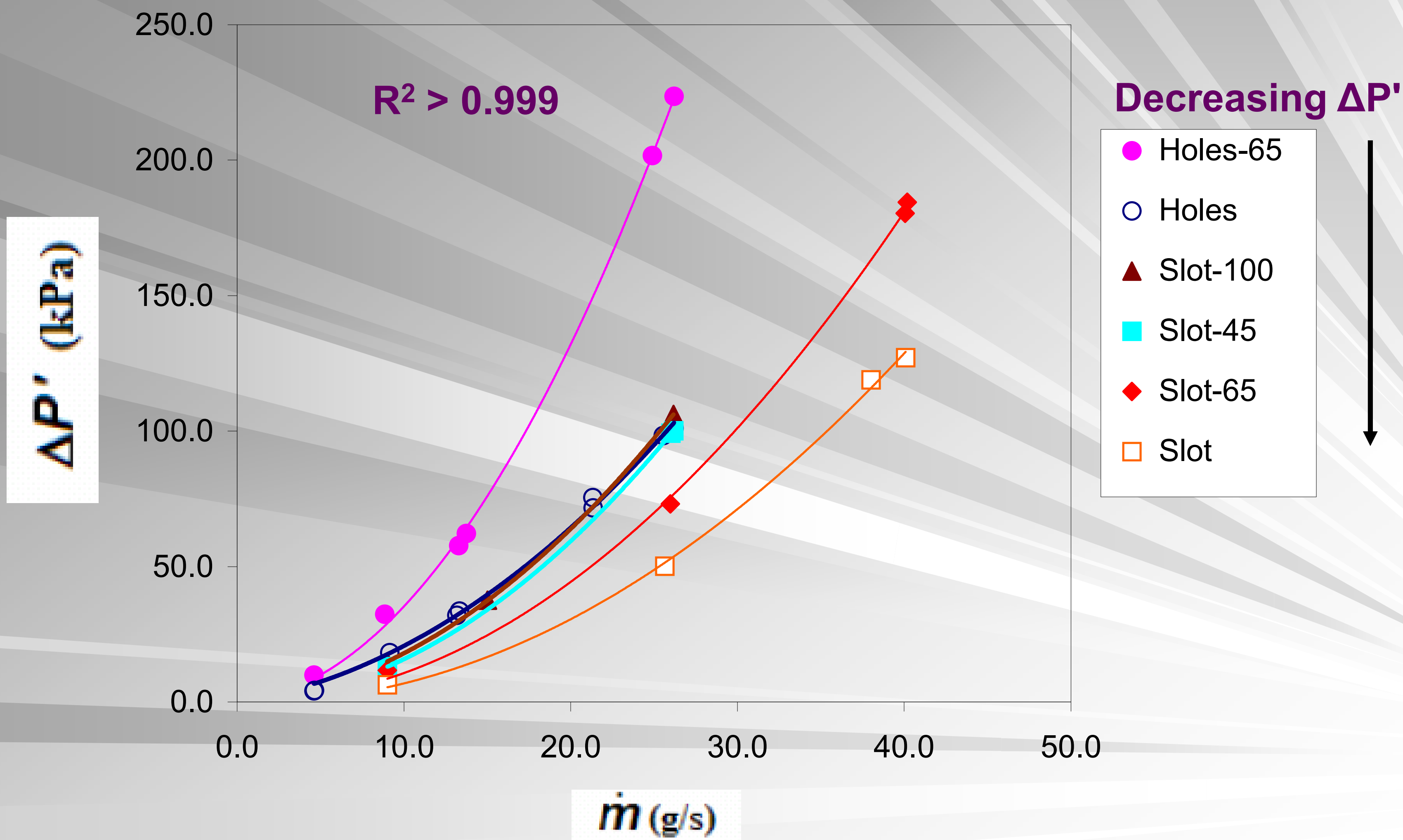
20%

42%

51%

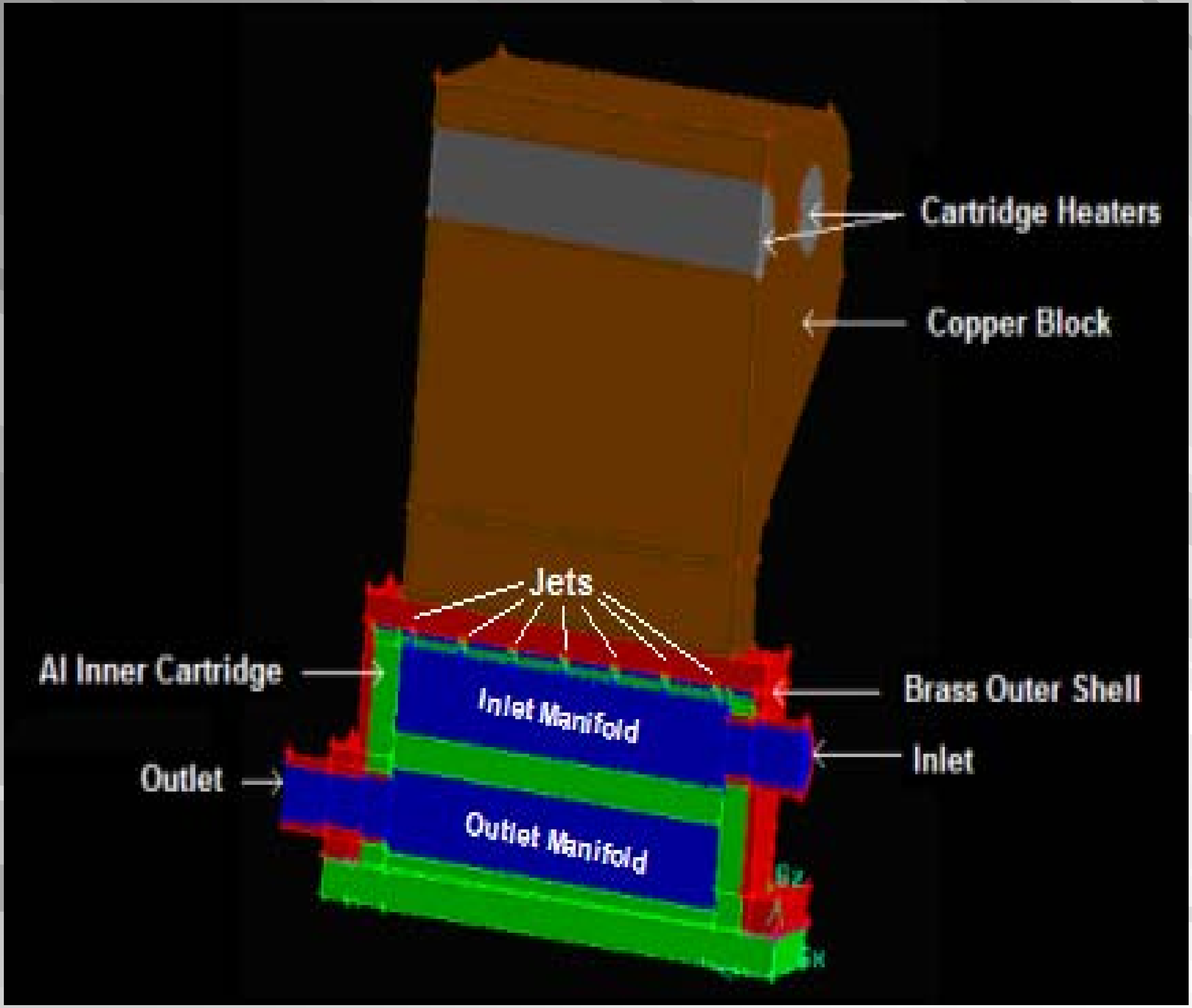
Normalized Pressure Drop



Comparison Between Test Configurations

MFR = 9 g/s	ΔP' (kPa)	% Inc. ΔP' (-)	h_{avg} (W/m^2-K)	% Inc h_{avg} (-)
Slot-100	14.8	136%	2875	71%
Slot-65	11.7	87%	2554	52%
Holes-65	32.4	415%	2363	40%
Holes	18.2	190%	2080	24%
Slot-45	13.0	107%	1945	16%
Slot	6.3	-	1682	-
MFR = 26 g/s				
Slot-100	106.2	112%	4476	51%
Holes-65	223.6	346%	4353	47%
Slot-65	73.1	46%	4207	42%
Holes	101.1	102%	4081	37%
Slot-45	99.2	98%	3573	20%
Slot	50.2	-	2970	-

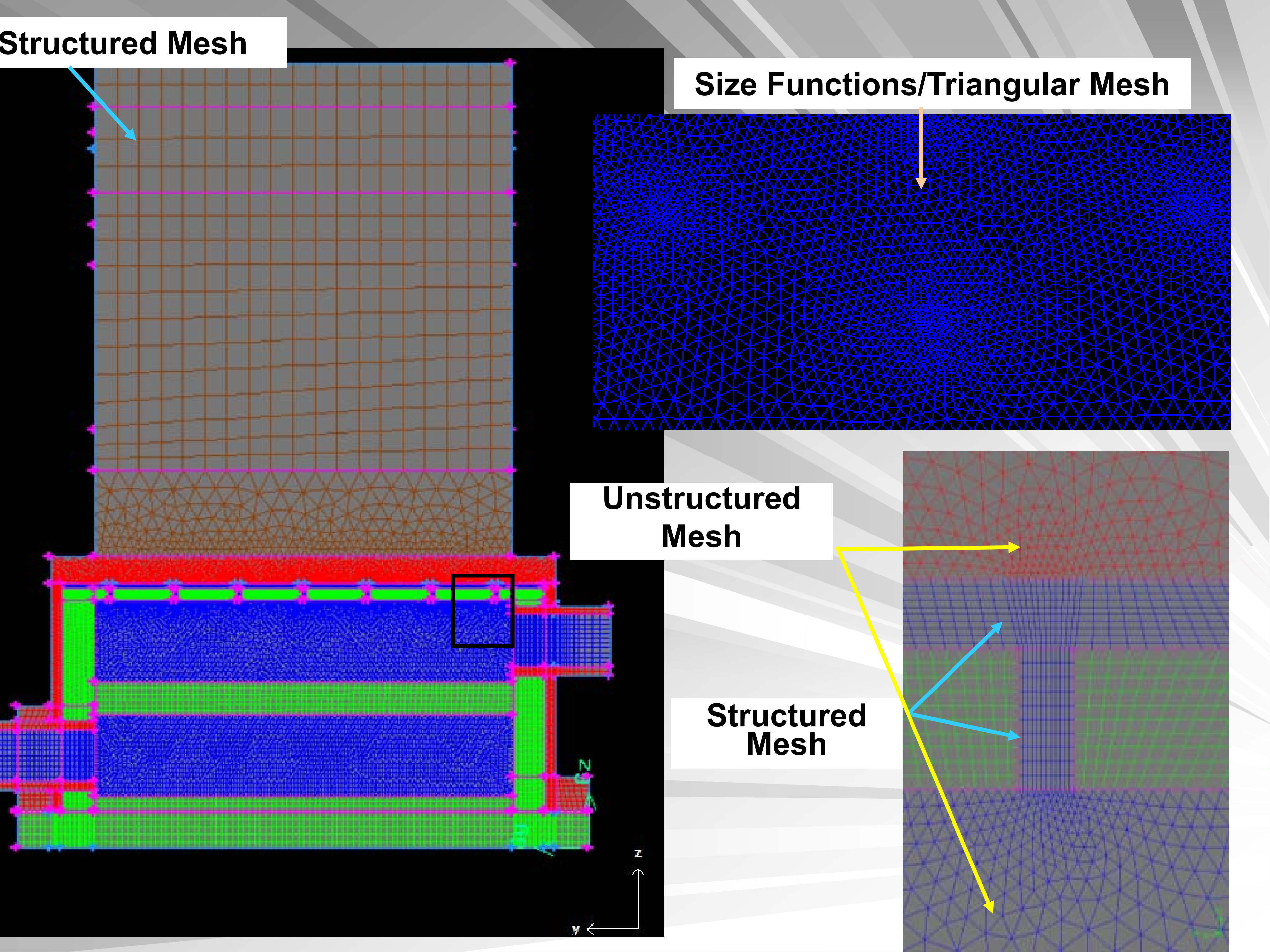
Numerical Model



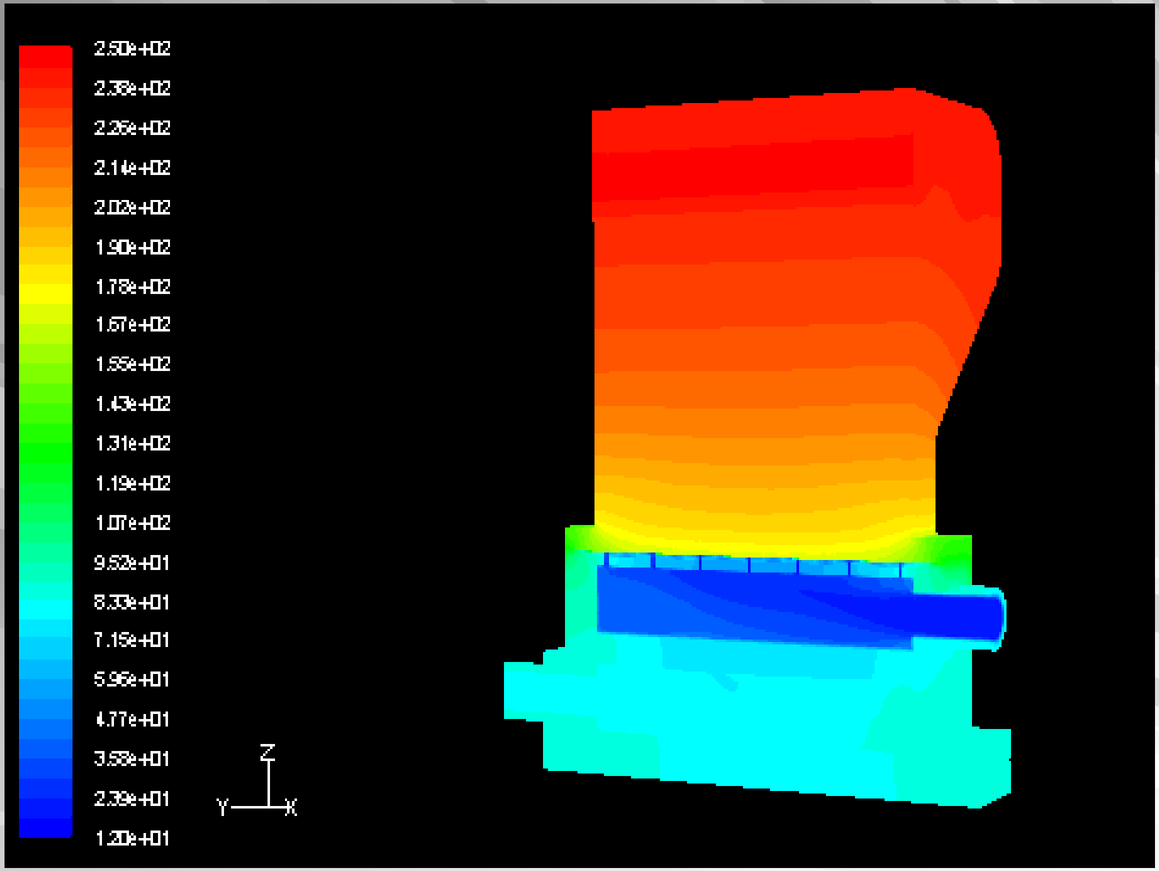
Gambit® 2.2.30
FLUENT® 6.2

Half-model via symmetry

1.67×10^6 cells
7.66×10^5 nodes

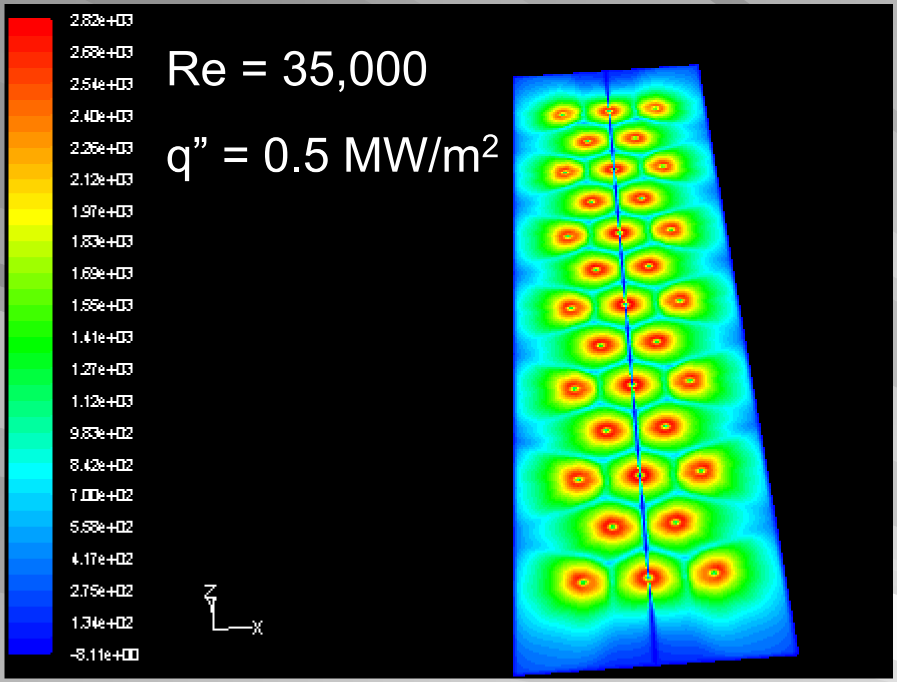

Structured Mesh
Size Functions/Triangular Mesh
Unstructured Mesh
Structured Mesh
z
y

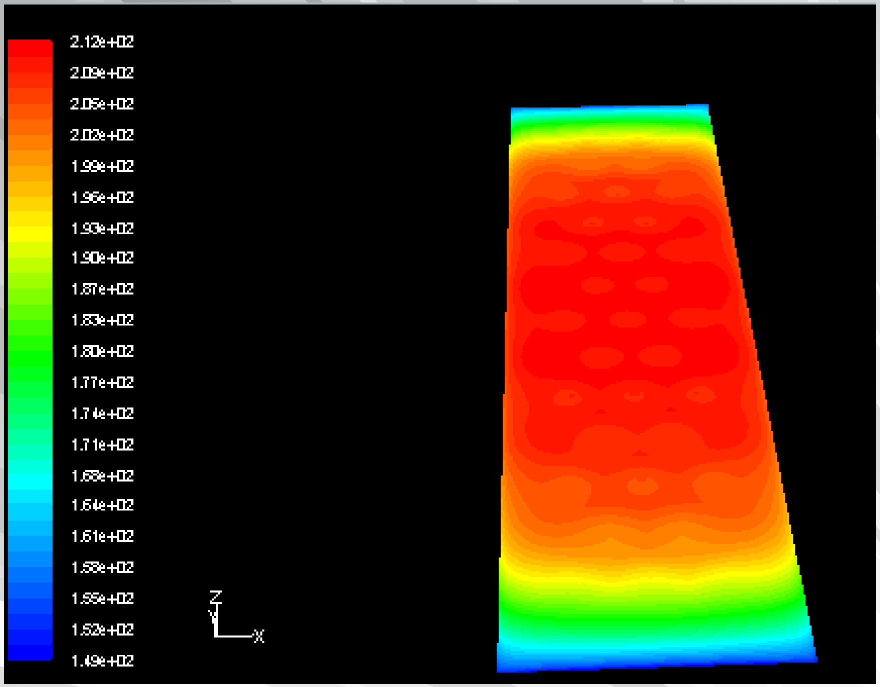
Results – Temperature Contours



Uniform incident heat flux in center of concentrator (*Re* = 35,000)

Results - HTC & Temp. Profiles



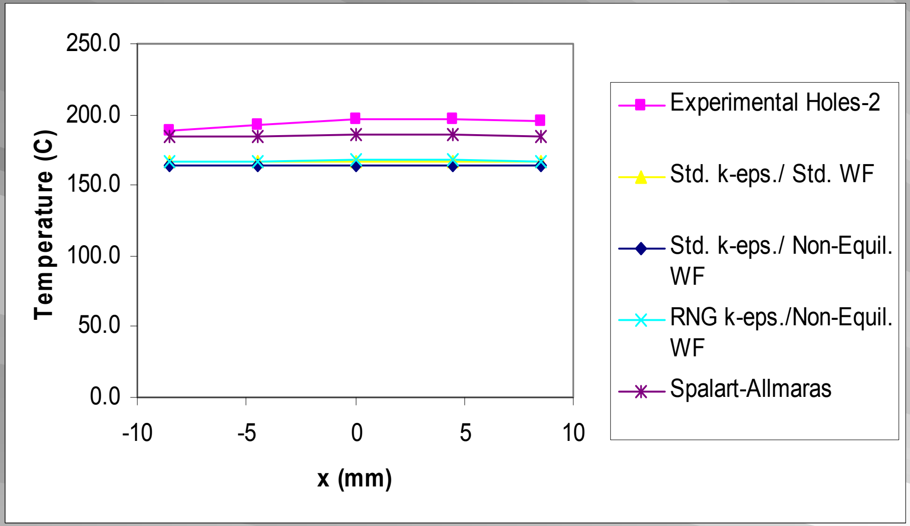


- h_{max_air} = 2.82 kW/m^2-K → h_{max_He} = 34.1 kW/m^2-K
- h_{avg_air} = 1.25 kW/m^2-K → h_{avg_He} = 15.1 kW/m^2-K

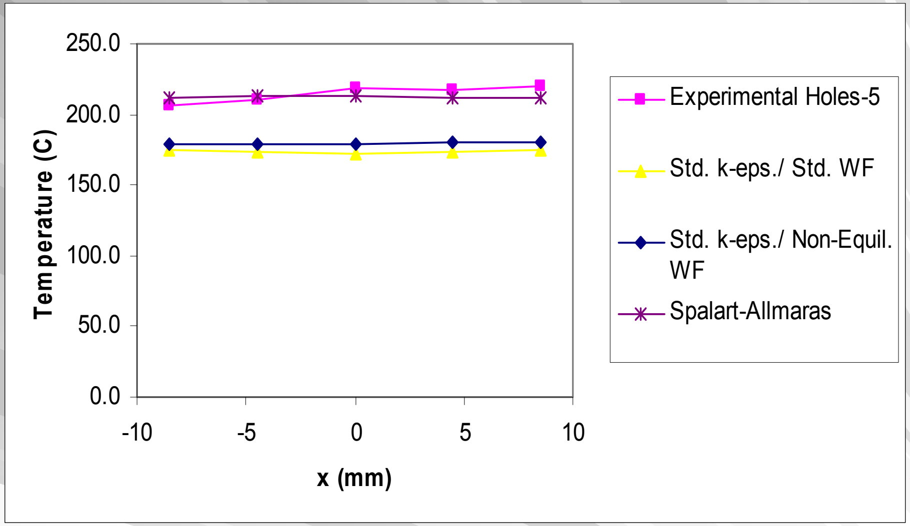
$$\boxed{h_{He} = \frac{k_{He}}{k_{air}} * h_{air} = 12.1 * h_{air}}$$

FLUENT vs. Experimental

Low Flow/ Low Power



Medium Flow/ Medium Power



- k-ε turbulence model overpredicts HTC by ~15% for the low flow case and ~20% for the medium flow case
- Spalart-Allmaras turbulence model overpredicts HTC by ~5% for low flow case and ~2% for the medium flow case

Summary – Flat Plate Divertor Study

- Experimentally examined thermal performance of a prototypical flat-plate divertor module
- Six variations of the flat-plate divertor concept were studied and evaluated in terms of heat transfer coefficient and pressure drop
- These results provide a key dataset for validating commercial CFD codes and models

Conclusions and Contributions

- **Designed and constructed experimental test modules duplicating complex geometries of leading three He-cooled divertor designs**
- **Conducted experiments at dynamically-similar conditions matching/spanning expected prototypical operating conditions**
- **Constructed detailed numerical models with commercial CFD software to predict performance of experimental Apparatuses**
- **Good agreement between experimental and numerical results**
  - Results confirm validity of high heat transfer coefficients predicted in preliminary design calculations
  - Confirmed that these divertor designs can accommodate incident heat flux values up to 10 MW/m^2
- **Validated CFD Codes can be used with confidence to predict performance of gas-cooled components with complex geometries**
  - Optimize/modify design and/or operating conditions
  - Quantify sensitivity of performance to changes in operating conditions and/or geometry due to manufacturing tolerances