Studies of Finger-Type Divertors with Helium: Initial Results

M. Yoda, S. I. Abdel-Khalik, D. L. Sadowski,
B. H. Mills, and J. D. Rader
G. W. Woodruff School of Mechanical Engineering

Georgia Institute of Technology

Objectives / Motivation

Objectives

- Evaluate thermal performance of gas-cooled divertor designs in support of the ARIES team
  - Develop generalized charts for estimating maximum heat flux and pumping power requirements
  - Verify that dynamically similar air experiments can be extrapolated to prototypical conditions with helium

Motivation

- Provide design guidance and develop correlations that can be used in system codes
- Divertors may have to accommodate steady-state and transient heat flux loads exceeding current design limits of 10 MW/m^2

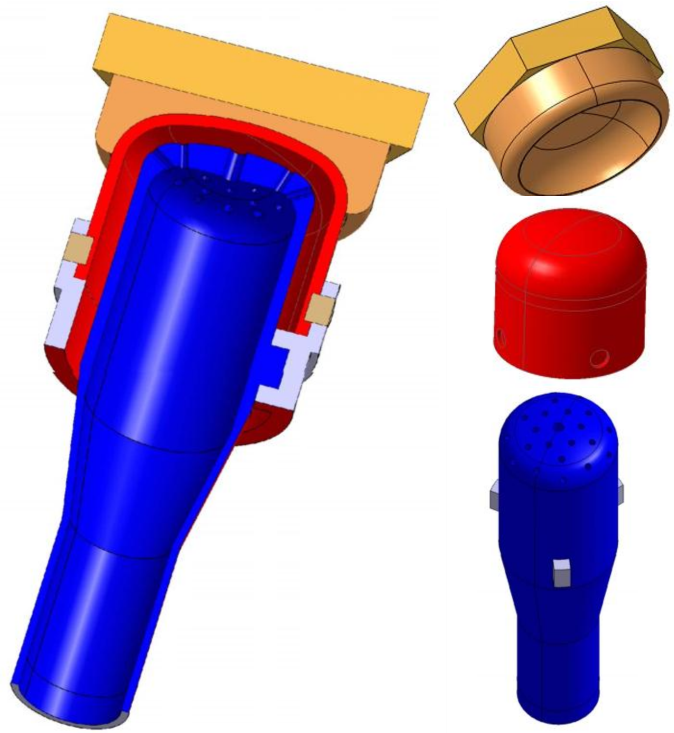
Approach

- Design and instrument test modules that closely match divertor geometries
- Conduct experiments that span expected non-dimensional parameters at prototypical operating conditions
  - Reynolds number *Re*
  - ***Use air instead of He***: difference in Prandtl numbers has negligible effect on Nusselt number *Nu*
- Measure cooled surface temperatures and pressure drop
  - Calculate *Nu* and loss coefficients to extrapolate to use with He at prototypical operating conditions
- Validate non-dimensional approach by conducting experiments with helium

Finger-Type Divertors

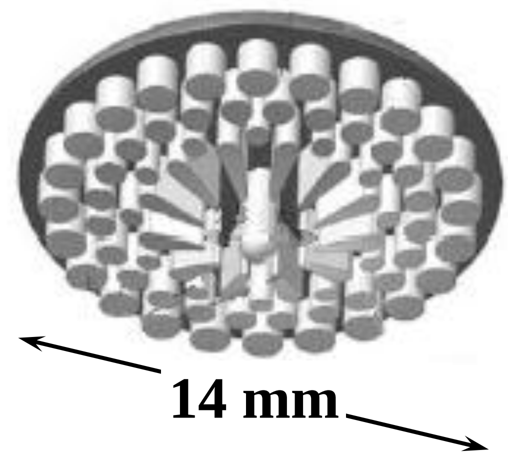
- Can accommodate heat fluxes exceeding 10 MW/m^2
- Cover small area: ~5×10^5 modules for O(100 m^2) divertor

HEMJ



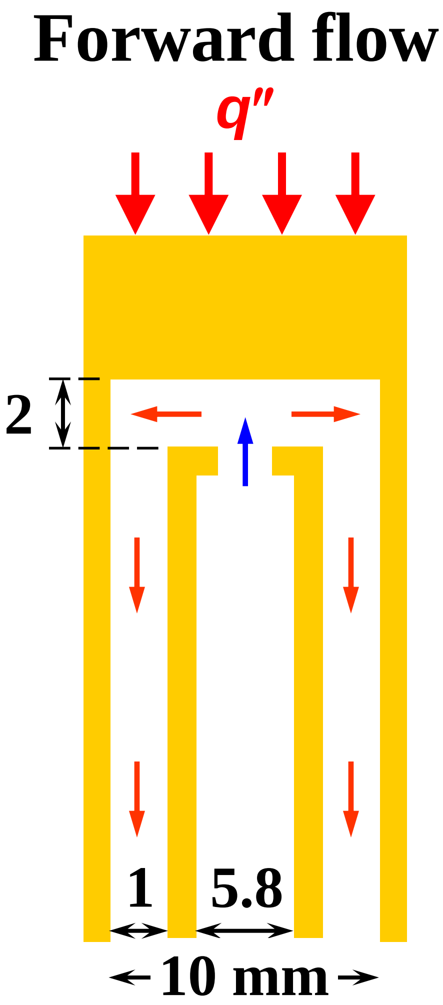
HEMP

[Diegele *et al*. 2003;
Norajitra *et al*. 2004;
Ihli 2005]

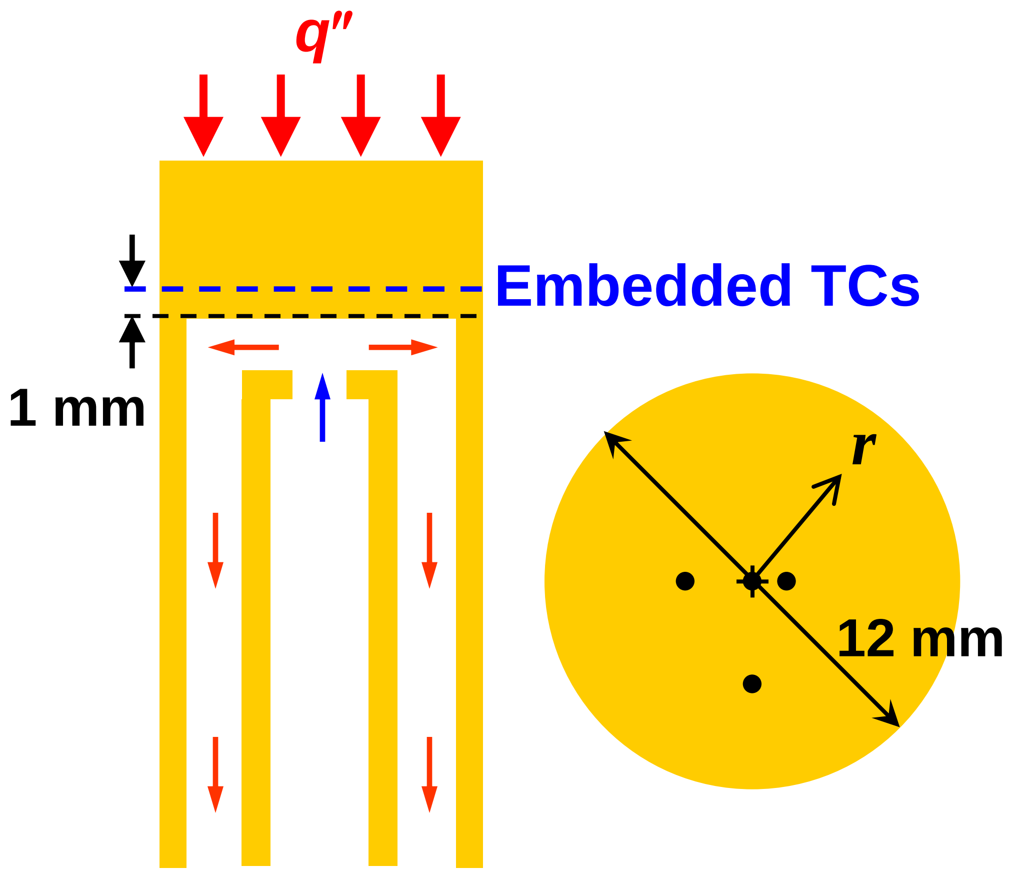


GT Test Module

- Coolants: air, helium (He), argon (Ar)
  - Operating *Re* range: ~$8\times10^3 - 1.5\times10^5$
  - He, Ar supplied by gas cylinders
- Test module fabricated in brass
  - Thermal conductivity *k* similar to W
  - Heated by oxy-acetylene torch: $q'' \leq 2.0$ MW/m^2
  - Forward flow: one round jet with exit diameter d_j = 2 mm impinges on cooled surface, then flows through annular gap
  - Measure coolant temperatures at inlet, exit (T_i, T_e); inlet pressure $p_i \leq 1.4$ MPa and pressure drop Δp across test module
  - Measure coolant mass flow rate $\dot{m}$



Cooled Surface Temps.



- Four type-E thermocouples (TC) embedded 1 mm from the cooled surface
  - Cooled surface TCs: r = 0, 1, 2 and 3 mm
- Extrapolate TC readings to determine temperature at cooled surface ⇒ average cooled surface temperature T_c

Calculating HTCs

- Average heat flux: energy balance based on coolant properties

$$q'' \equiv \dot{m}\,\overline{c}_{\mathrm{p}}(T_{\mathrm{e}} - T_{\mathrm{i}}) / A$$

- Average heat transfer coefficients (HTCs)

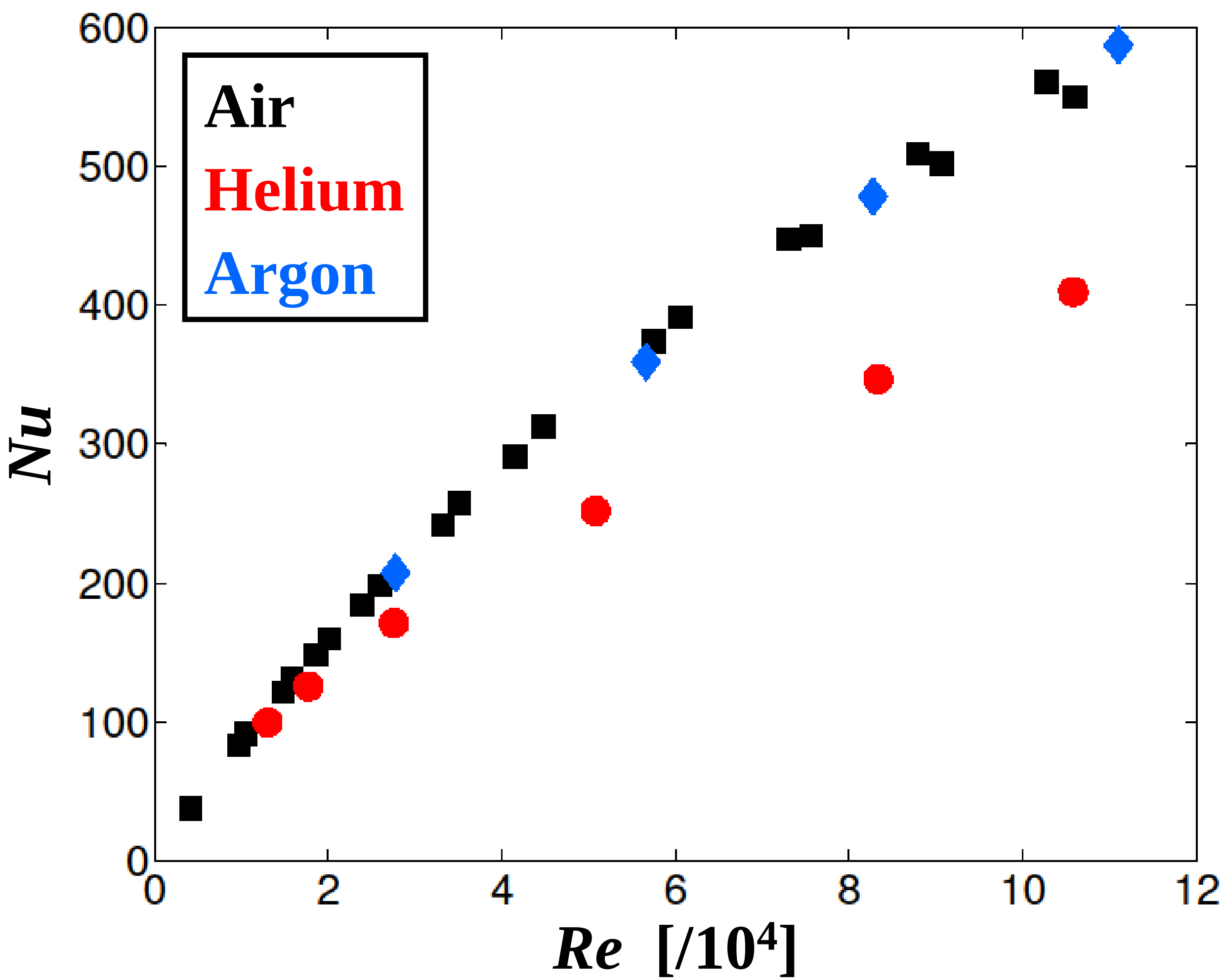
$$h = \frac{q''}{T_{\mathrm{c}} - T_{\mathrm{i}}} \frac{A}{A_{\mathrm{c}}}$$

- Average Nusselt number

$$Nu = \frac{h d_{\mathrm{j}}}{k}$$

  - A = 113 mm^2 area of heated (outer) surface of pressure boundary
  - $\overline{c}_{\mathrm{p}} = [c_{\mathrm{p}}(T_{\mathrm{i}}) + c_{\mathrm{p}}(T_{\mathrm{e}})] / 2$
  - A_{c} = 78.5 mm^2 area of cooled (inner) surface
  - k evaluated at average coolant temperature $T_{\mathrm{av}} = (T_{\mathrm{i}} + T_{\mathrm{e}})/2$

Nu Results: Air, He, Ar



- Nusselt numbers from He experiments consistently lower than those for air
  - Results for Ar similar to those for air
  - Why are the He results different from those for air and Ar?

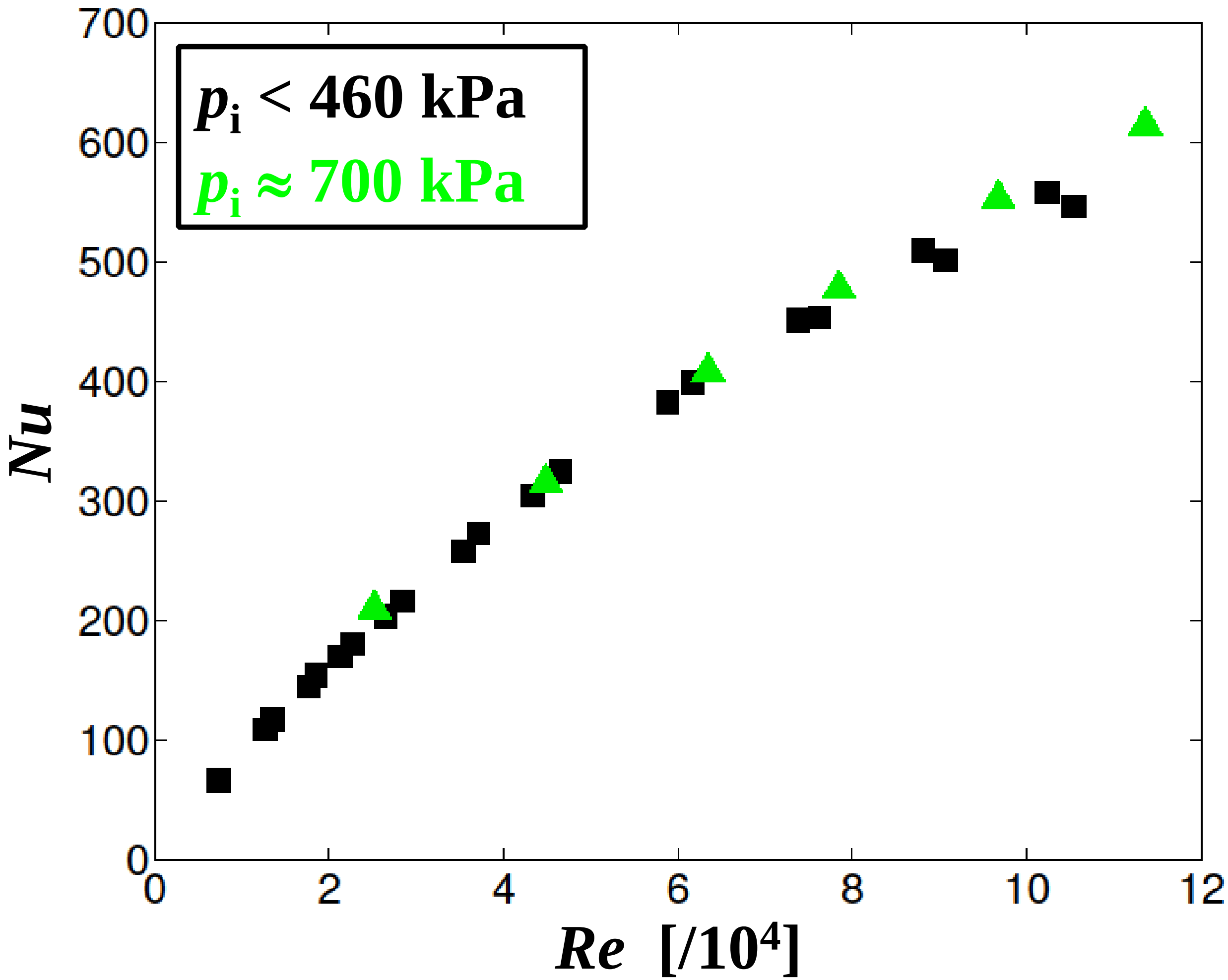
Compressibility Effects

- Does compressibility affect *Nu*?
- Calculate average jet Mach number *Ma* for each gas at its highest *Re* for uniform flow across the jet exit:

$$Ma = \frac{\dot{m}}{\rho(\pi d_j^2 / 4)} \frac{1}{\sqrt{\gamma R T_i}}$$

  - *Ma* = 0.46, 0.49 and 0.43 for air, He, and Ar, respectively
  - Little variation in *Ma* between coolants, but *Ma* > 0.3, so compressibility may matter
- To determine if compressibility affects these results, compare results from two sets of experiments with air at same *Re*:
  - Control *Re* by varying inlet pressure p_i, where $p_i < 420$ kPa
  - Control *Re* by varying pressure drop Δp at fixed $p_i \approx 700$ kPa

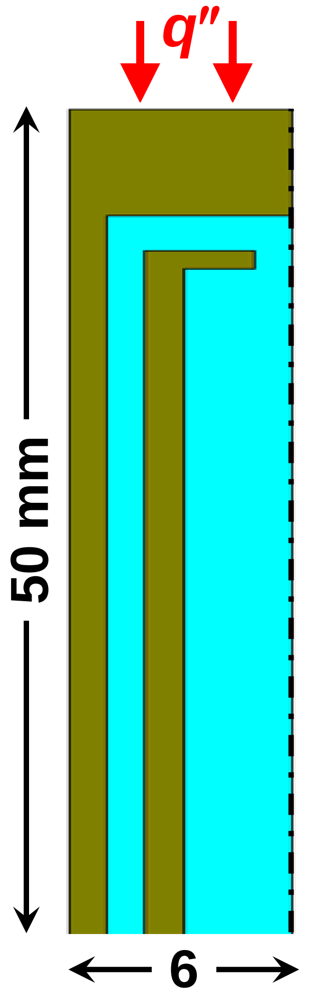
Compressibility



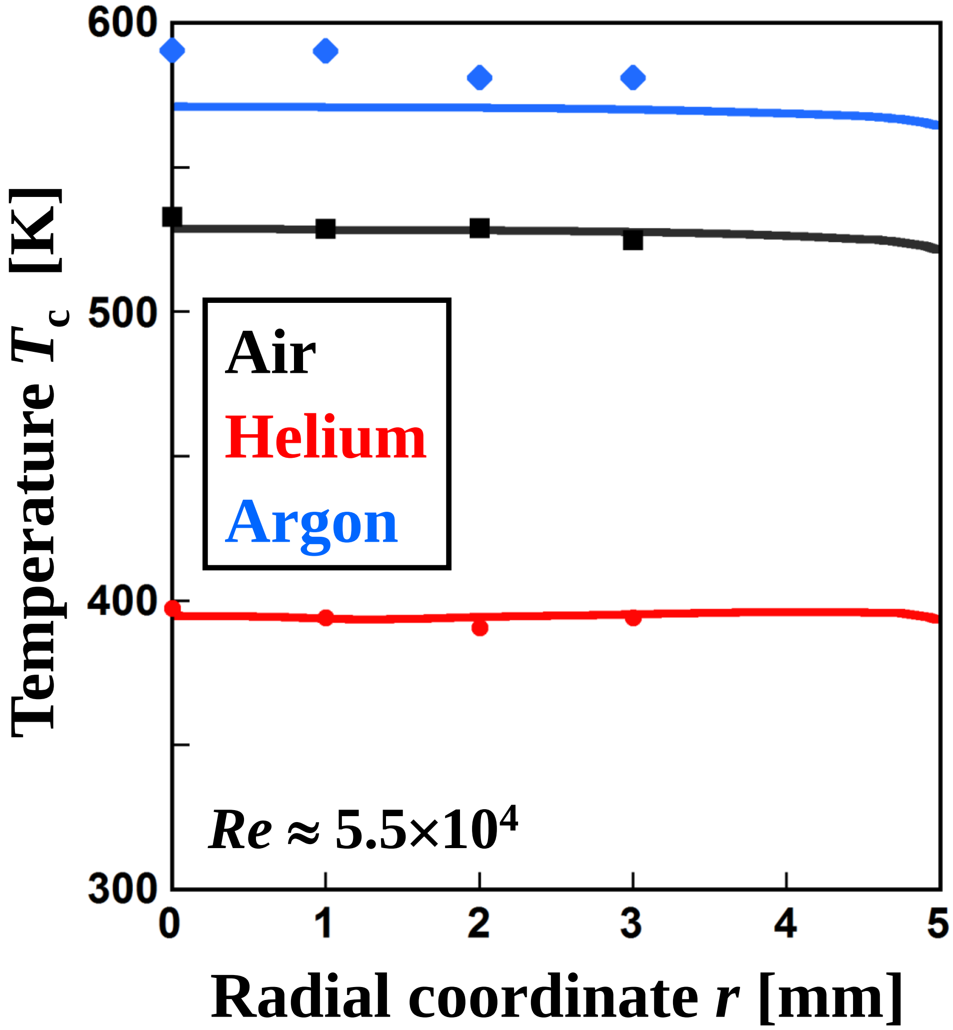
- Both sets of experiments give same *Nu*(*Re*)
- Both sets of experiments have very different *Ma*:
  - For p_i < 460 kPa, *Ma* = 0.15–0.45
  - For p_i ≈ 700 kPa, *Ma* = 0.07–0.36
- Compressibility does not affect *Nu*

Numerical Simulations

- Use numerical simulations that match the experimental conditions to investigate why He and air results for *Nu*(*Re*) are different
  - Look at velocity, temperature and HTC distributions: ***local*** values
- Commercial CFD software: ANSYS FLUENT® v13.0
  - Spalart-Allmaras turbulence model
- 2D axisymmetric model of test module
  - Nonuniform mesh of ~4×10^5 triangular cells generated with Gambit v2.4.6
  - Finest spatial resolution of 30 μm at cooled surface

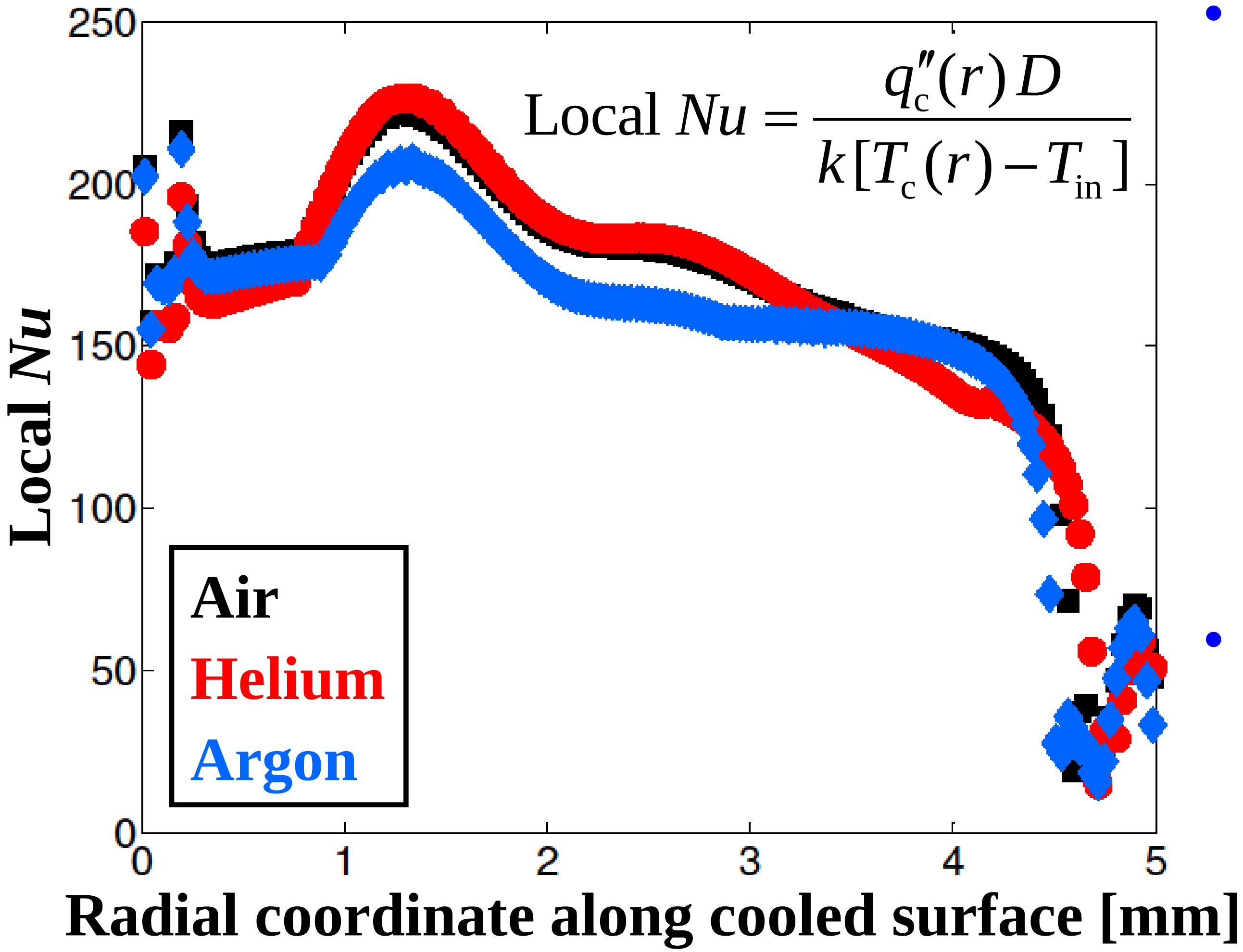


Boundary Conditions



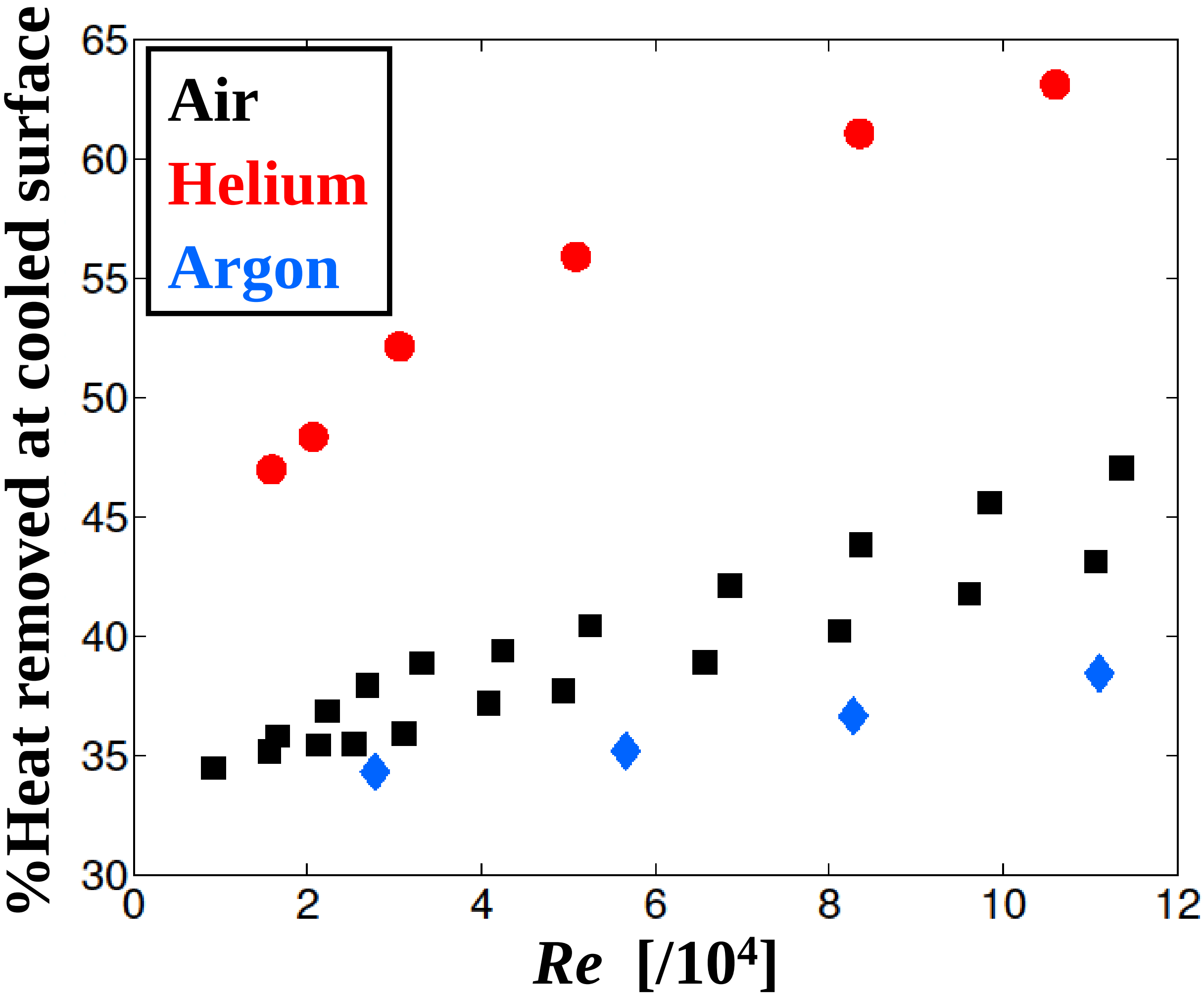
- To match experiments, match T_i, $\dot{m}$, $p_e \equiv p_i + \Delta p$, q''
  - Adiabatic boundary conditions at outer walls
- Calculate <u>local</u> heat flux $q_c''(r)$ due to conduction through 6 mm brass between heated, cooled surfaces
- Numerical predictions of temperature distribution over cooled surface $T_c(r)$ in good agreement with TC readings for air, He, Ar

Local *Nu* at *Re* ≈ 5.5×10⁴



- Radial profiles of **local** *Nu* similar for air, He
  - Contradicts **average** *Nu* results
  - Local *Nu* based on experimental estimates of q''
- Does the wall conduction contribution differ for different coolants?

Conduction *vs.* Convection



- Compare heat removed by coolant with q_c'' from simulations
  - He removes most heat, *i.e.* has highest fraction of convective heat transfer
  - Majority of heat transferred by conduction for air, Ar

Dimensional Analysis

- If conduction is significant, the HTC must also depend upon the thermal conductivity of the solid material of the finger, k_s, as well as that of the coolant k

$$h = f(\rho, \mu, c_p, k, V, d_j, \mathbf{k_s})$$

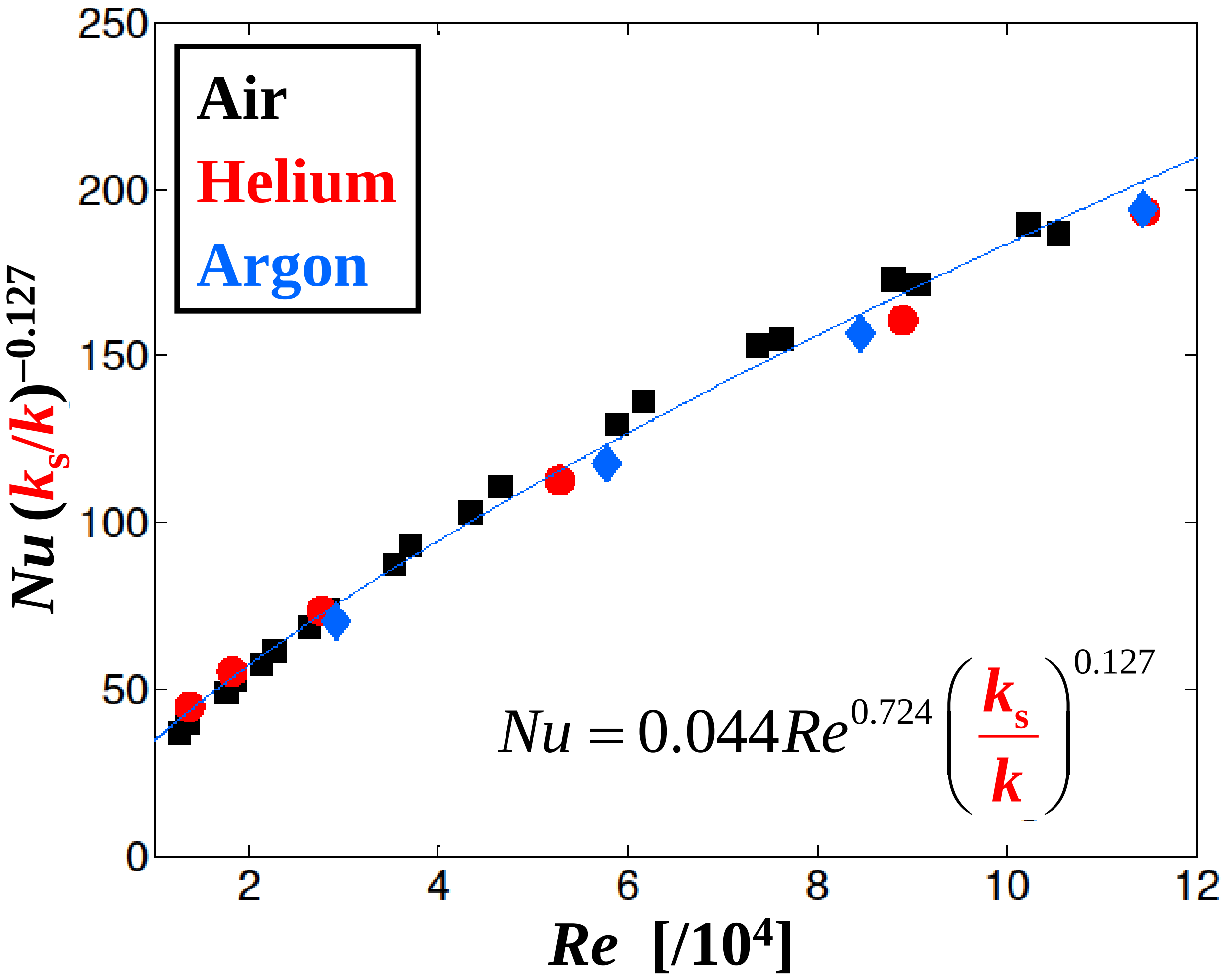
- By Buckingham Pi Theorem, the nondimensional HTC, or Nusselt number, depends upon a new dimensionless group, the ratio of the thermal conductivities

$$Nu = \phi(Re, Pr, \mathbf{k_s / k})$$

- Assume that *Nu* has a power-law dependence on *Re* and the new dimensionless group (*Nu* is assumed to be independent of *Pr*)

$$Nu \propto Re^i \left(\frac{\mathbf{k_s}}{\mathbf{k}} \right)^j$$

Modified *Nu* Correlation

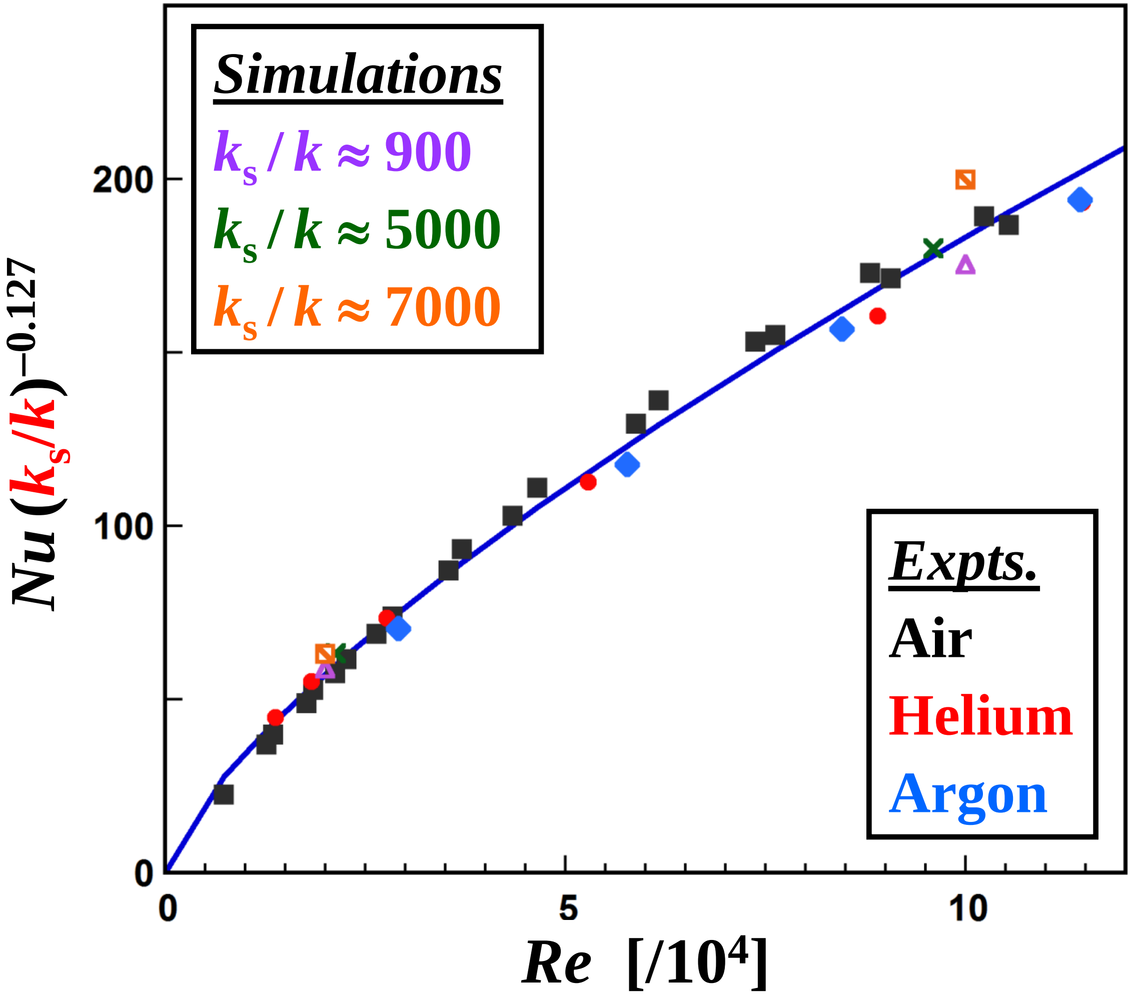


- By accounting for the fraction of heat removed by conduction (by including k_s / k), the *Nu* results for all three gases are well-described by a single correlation

Further Validation

- Experiments (at fixed k_s) consider only three values of k_s / k: ~900, ~5000, and ~7000 for He, air and Ar, respectively
- To verify that the correlation holds for $900 \leq k_s / k \leq 7000$, initial numerical simulations performed with air as a coolant for different values of k_s (*i.e.*, different finger materials) at the lowest and highest *Re* of interest: $Re \approx 2\times10^4$ and 10^5
  - Additional simulation at $k_s / k = 5000$ to validate experiments
- For W alloy (1% La_2O_3) at 600 °C–1300 °C and He at 600 °C–800 °C, $k_s / k \approx 290$–400
  - Prototypical conditions outside range of experiments
- Need to extend parameter range of correlation

Validation Results



- Simulation results at $Re \approx 2\times10^4$ and 10^5 in good agreement with correlation for all values of k_s / k

$$Nu = 0.044 Re^{0.724} \left(\frac{k_s}{k} \right)^{0.127}$$

  - Can use such correlations to estimate max. q'' at prototypical conditions

Summary

- Performed experimental studies of finger type divertor with helium and argon to verify similarity to experimental results obtained with air
  - *Nu* is not only a function of *Re* and *Pr*: must also account for relative importance of conduction *vs.* convection by ratio of thermal conductivities k_s / k
  - Compressibility effects negligible
- Initial results suggest that power-law correlation can be used for all three coolants
  - Preliminary results suggest similar trends for other flow configurations, including those with cylindrical fins
  - Further experiments and simulations required to extend correlation to prototypical conditions

$$Nu = C\,Re^{i}\left(\frac{k_s}{k}\right)^{j}$$