Effects of Thermal Conductivity Ratio in Helium-Cooled Divertors

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Objectives and Background

Objectives

- Experimentally verify dynamic similarity of experiments of a finger-type divertor module performed with different coolants and different test section materials
  - Match nondimensional coolant flow rate and solid-to-coolant thermal conductivity ratio
- Verify previous predictions of thermal performance at prototypical conditions and general parametric design curves

Background

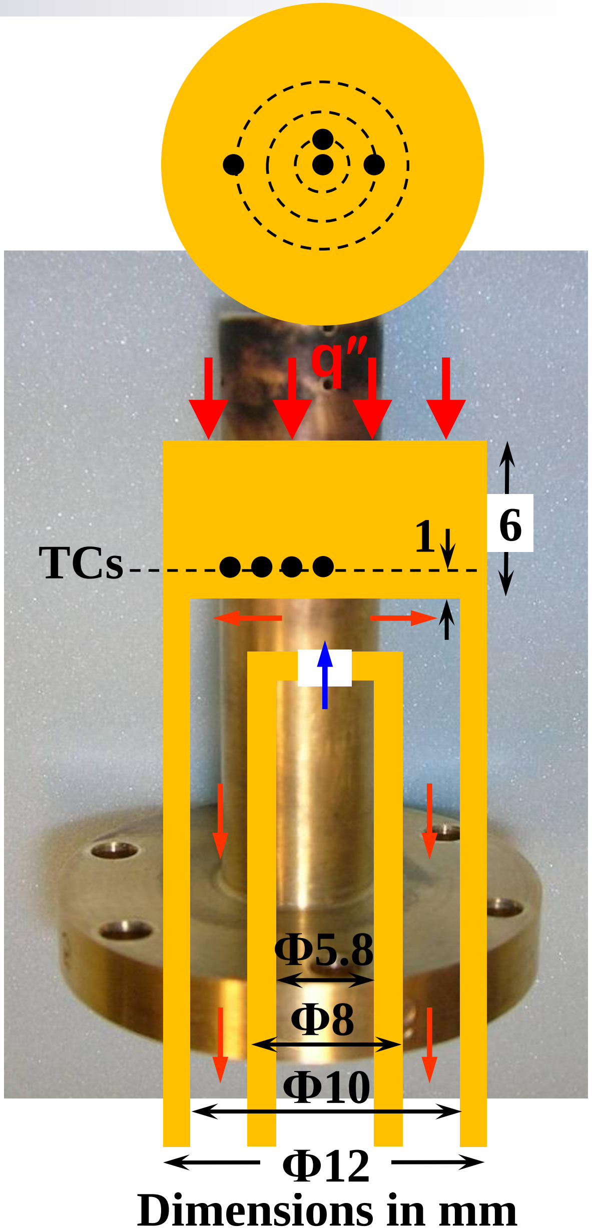
- Part of the ARIES study and GT effort on evaluating the thermal-hydraulics and improving the thermal performance of various helium-cooled divertor designs

Original Experimental Approach

- Fabricate and instrument test sections that closely simulate geometry of proposed divertor module
  - Heat test sections with oxyacetylene torch or electrical heaters
- Perform dynamically similar experiments spanning prototypical operating conditions with air instead of helium (He)
  - Match nondimensional coolant flow rate ⇔ Reynolds number *Re*
  - Prandtl and Mach number effects negligible
- Calculate nondimensional heat transfer coefficient $\overline{Nu}$ and loss coefficient K_L from experimental data
  - Measure surface temperature, pressure drop
- Extrapolate results to prototypical conditions: Tungsten-alloy module cooled by high-temperature He

GT Test Module

- Single jet-impingement design
  - Dimensions similar to HEMP
  - Constructed of C36000 brass alloy
  - Heated by oxy-acetylene torch at heat fluxes $q'' < 2.0$ MW/m^2
- Operating conditions determined from energy balance on HEMP design at 10 MW/m^2 $\Rightarrow$
  - $Re = 7.6\times10^4$ at central port
  - Experiments: $1\times10^4 < Re < 1.4\times10^5$
  - Coolants: air, Ar, and He
- Embedded thermocouples (TC) measure temperature near cooled surface



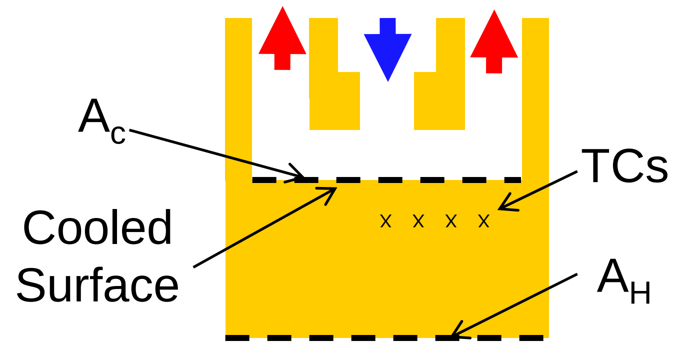
Calculating $\overline{Nu}$ and Re

- Determine Reynolds number from mass flow rate $\dot{m}$

$$Re = \frac{4\dot{m}}{\pi \mu D_o}$$

- Calculate average HTC

$$\bar{h} = \frac{\bar{q}''}{(\bar{T}_c - T_{in})} \frac{A_H}{A_c}$$

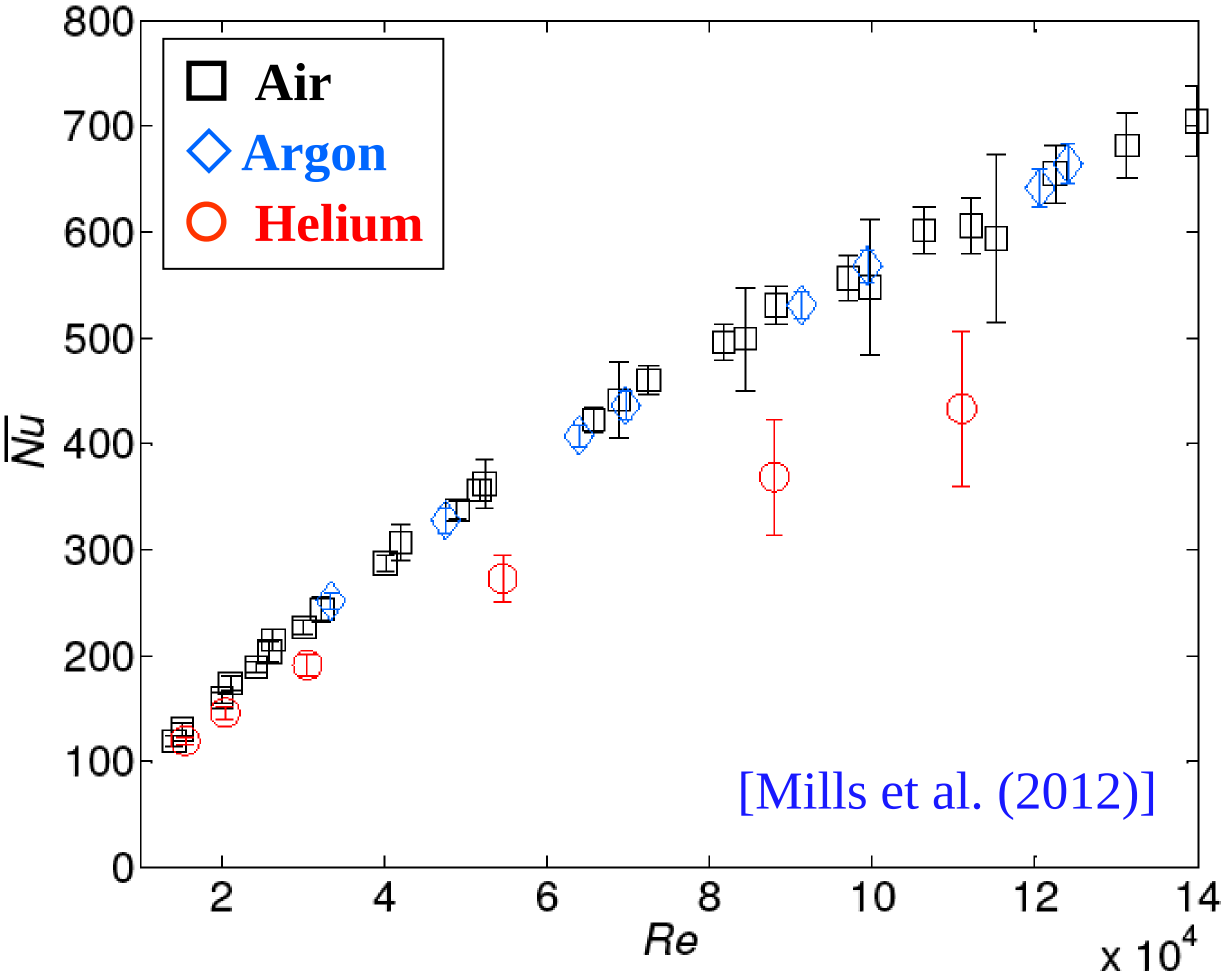


  - Average heat flux $\bar{q}''$ determined from energy balance for coolant
  - Avg. cooled surface temperature $\bar{T}_c$ extrapolated from embedded TC
- Determine nondimensional HTC, or average Nusselt number

$$\overline{Nu} = \frac{\bar{h} D_o}{k}$$

- Determine a correlation for $\overline{Nu}$ from these experimental data

Multi-Coolant Experiments



- Experiments performed with He and argon (Ar) to verify similarity
- $\overline{Nu}$ for He lower than those for air and Ar
  - But He has higher thermal conductivity *k*
- Matching *Re* not sufficient for similarity

Thermal Conductivity Ratio

- Numerical simulations (courtesy J. Rader) show that fraction of the incident heat flux removed by convection at cooled surface varies between different coolants

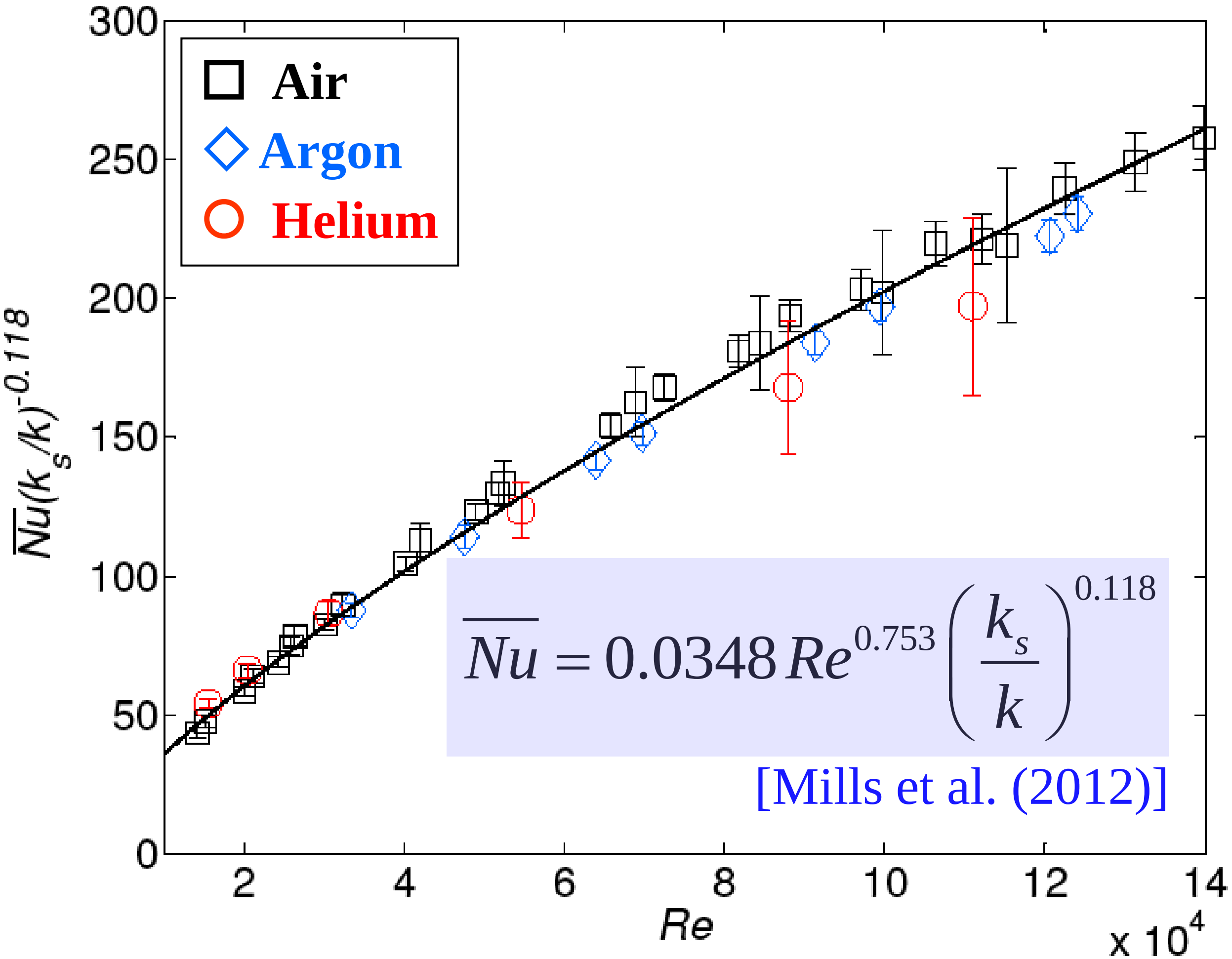
Coolant	*Re*	$\bar{T}_c$ (Expts.)	$\bar{T}_c$ (Simulations)	Removed heat
Air	4.94×10^4	291 °C	293 °C	**37.7 %**
Helium	5.09×10^4	121 °C	121 °C	**55.9 %**

- Dimensional analysis: fraction of heat removed by convection (*vs*. conduction through divertor wall) characterized by solid-to-coolant thermal conductivity ratio k_s / k
- Assume power-law correlation for $\overline{Nu}$

$$\overline{Nu} = A\,Re^{B}\,(k_s / k)^{C}$$

(still neglecting *Pr*, *Ma* effects)

Thermal Conductivity Ratio



$$\overline{Nu} = 0.0348\, Re^{0.753} \left(\frac{k_s}{k} \right)^{0.118}$$

[Mills et al. (2012)]

- Based on experimental results for He, air and Ar, $\overline{Nu}$ well-described by power-law correlation for Re and k_s / k
  - $10^4 < Re < 1.4 \times 10^5$
  - $Pr \approx 0.7$
  - $900 < k_s / k < 7000$, but only one value of k_s considered

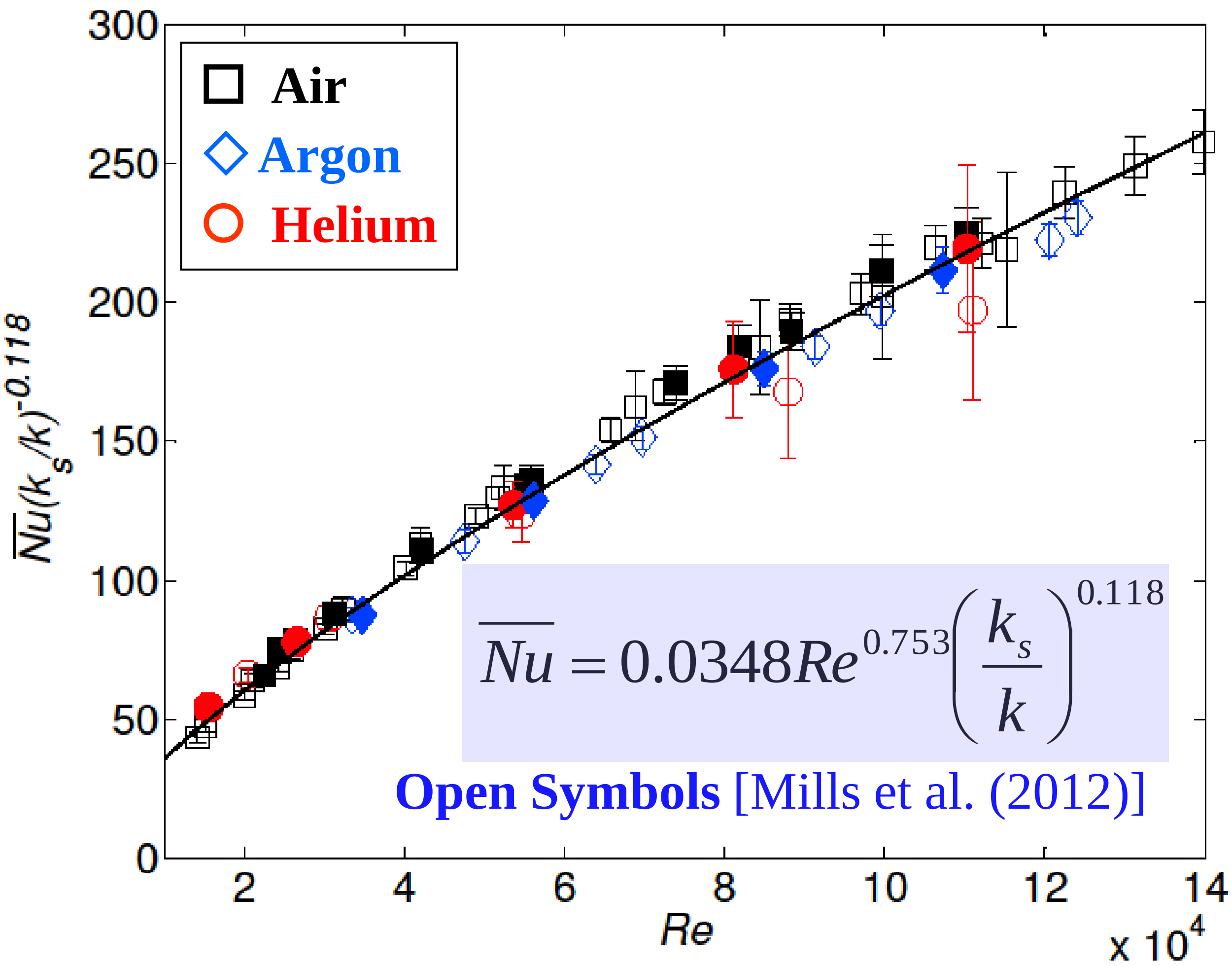
Thermal Conductivity Ratio

- $\overline{Nu}$ correlation experimentally validated for $900 < k_s / k < 7000$, all at one value of k_s

Test Section Material	k_s [W/(m-K)]	Coolant	k [W/(m-K)]	k_s / k
Brass	148 (at 300 °C)	Air	0.028 (at 50 °C)	5290
Brass	148 (at 300 °C)	He	0.16 (at 35 °C)	925
W-1%La_2O_3	116 (at 1000 °C)	He	0.34 (at 650 °C)	~340
Carbon steel	55 (at 200 °C)	He	0.16 (at 35 °C)	~340

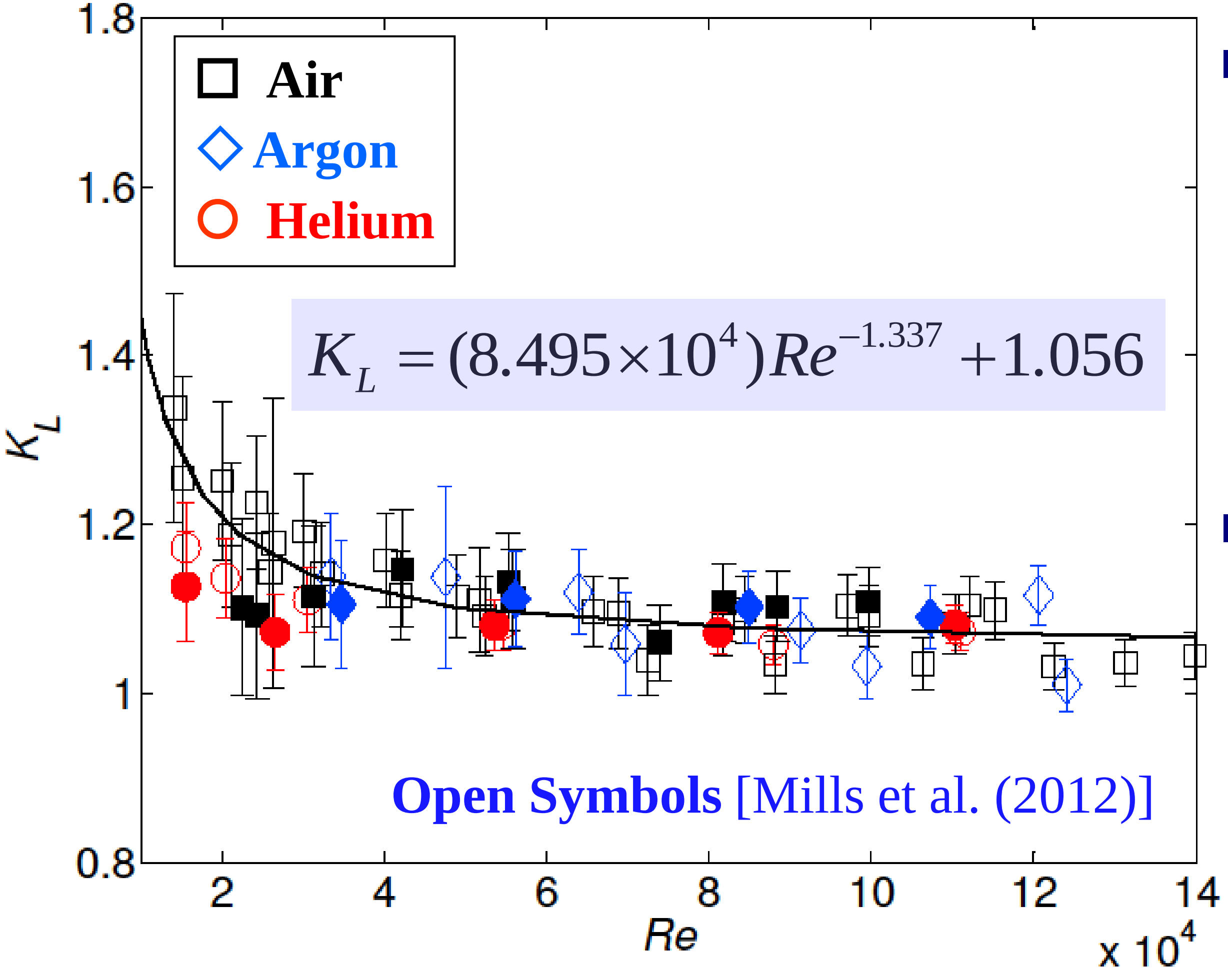
- Prototypical conditions (W-1%La_2O_3 cooled by He), $k_s / k \approx 340$
- Test section of AISI 1010 carbon steel cooled by He at near-ambient temperatures will also give $k_s / k \approx 340$
  - Twenty additional experiments performed with air, He, and Ar

Thermal Conductivity Ratio



- Experimental data from steel test section in excellent agreement with those for brass test section
- $\overline{Nu}$ correlation now experimentally confirmed for
  - $10^4 < Re < 1.2 \times 10^5$
  - $Pr \approx 0.7$
  - **350** $< k_s/k < 7000$

Loss Coefficient

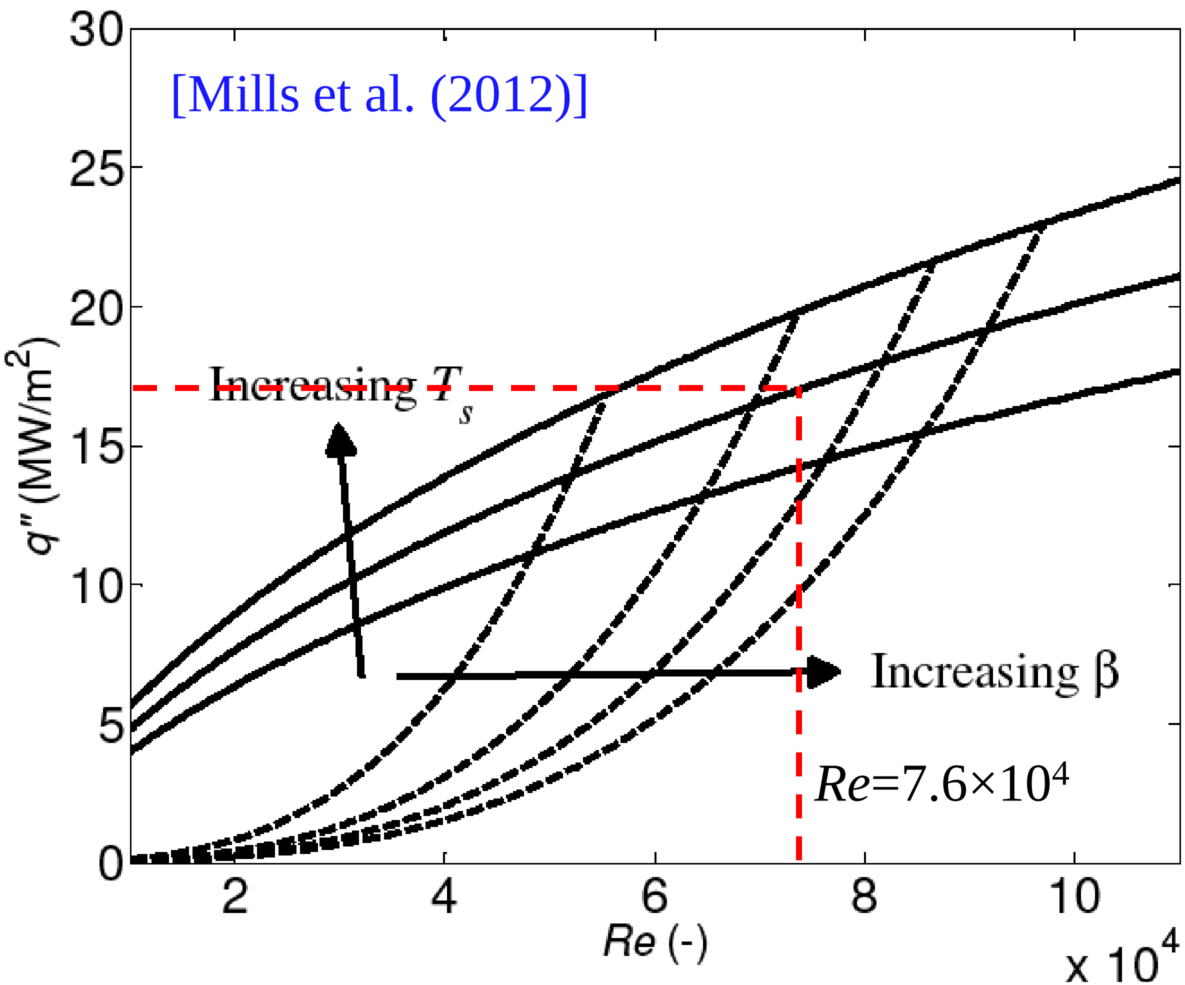


- Loss coefficient

$$K_L = \frac{\Delta p}{\rho \bar{V}^2 / 2}$$

  - ρ coolant density
  - $\bar{V}$ average speed at central port
- As expected, results for steel and brass test sections in excellent agreement since K_L hydraulic parameter

Maximum Heat Flux Charts



- Experimentally validated for prototypical conditions
  - He/W-1%La_2O_3
  - T_i = 600 °C
  - T_s = 1100 °C, 1200 °C, 1300 °C
  - β = 5%, 10%, 15%, 20%
- At $Re = 7.6\times10^4$, T_s = 1200 °C
  - q''_{max} = 17.3 MW/m^2
  - On tile: q''_T = 12.4 MW/m^2 for $A_T = 1.4\,A_h$

Summary

- Experimentally verified correlation for $\overline{Nu}(Re, k_s / k)$ at prototypical values of Re and k_s / k
  - Steel test section cooled by He at near-ambient temperatures gives $k_s / k \approx 350$: value for W-1%La_2O_3 divertor cooled by He at 600 °C
  - Experiments for steel test section cooled by air and Ar also in good agreement with previous results for brass test section

- Extrapolating these correlations to prototypical conditions gives:
  - At $Re = 7.6\times10^4$ and $T_s = 1200$ °C: $q''_{\max} = 17.3$ MW/m^2
  - Including a tile with $A_T = 1.4\,A_h$: $q''_T = 12.4$ MW/m^2