



Transition Regime Heat Conduction of Argon/Hydrogen and Xenon/Hydrogen Mixtures in a Parabolic Trough Receiver

Ph.D. dissertation
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Committee:

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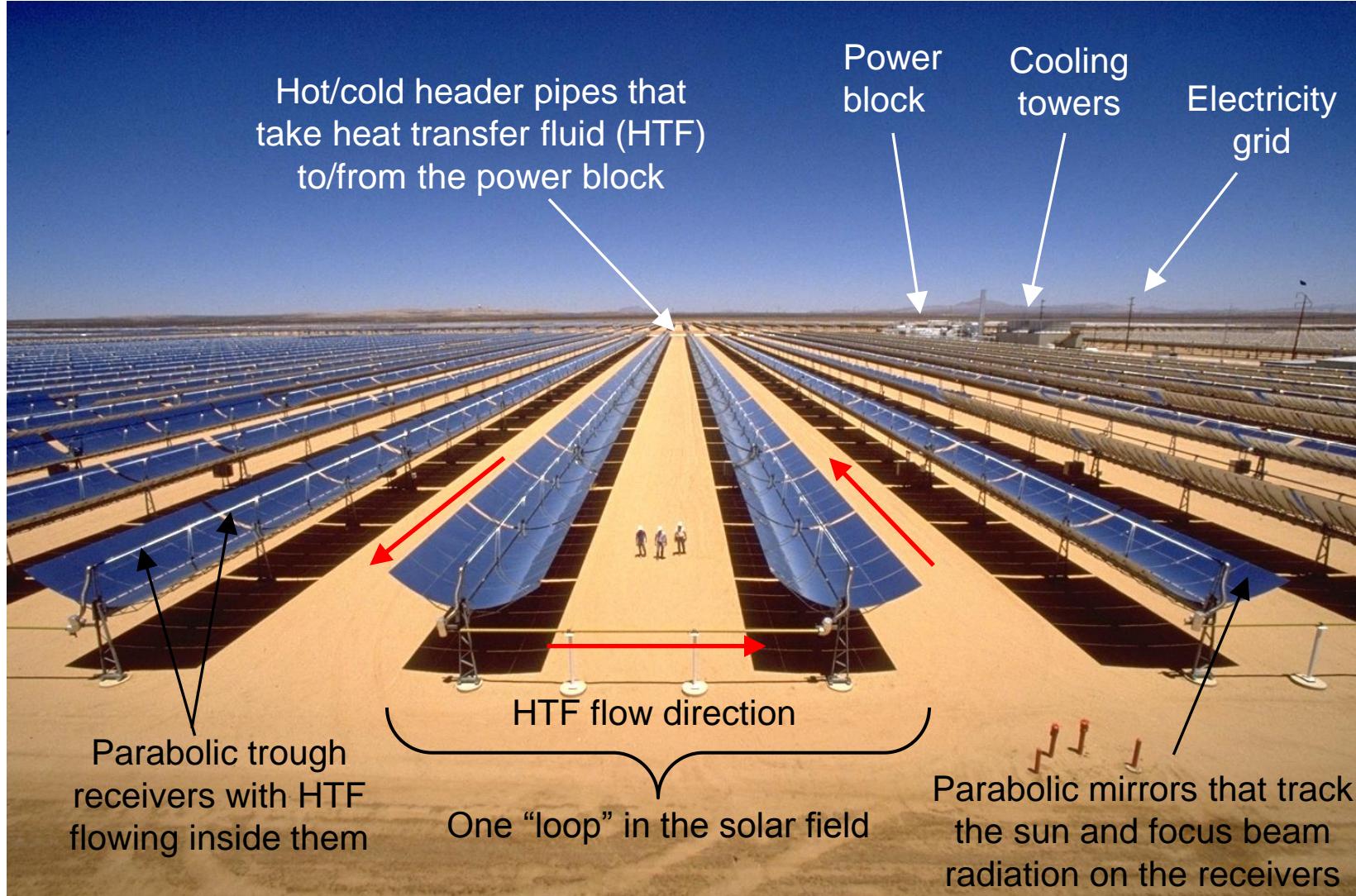
Dr. Chuck Kutscher Dr. Ed Wolfrum
National Renewable Energy Lab

Outline

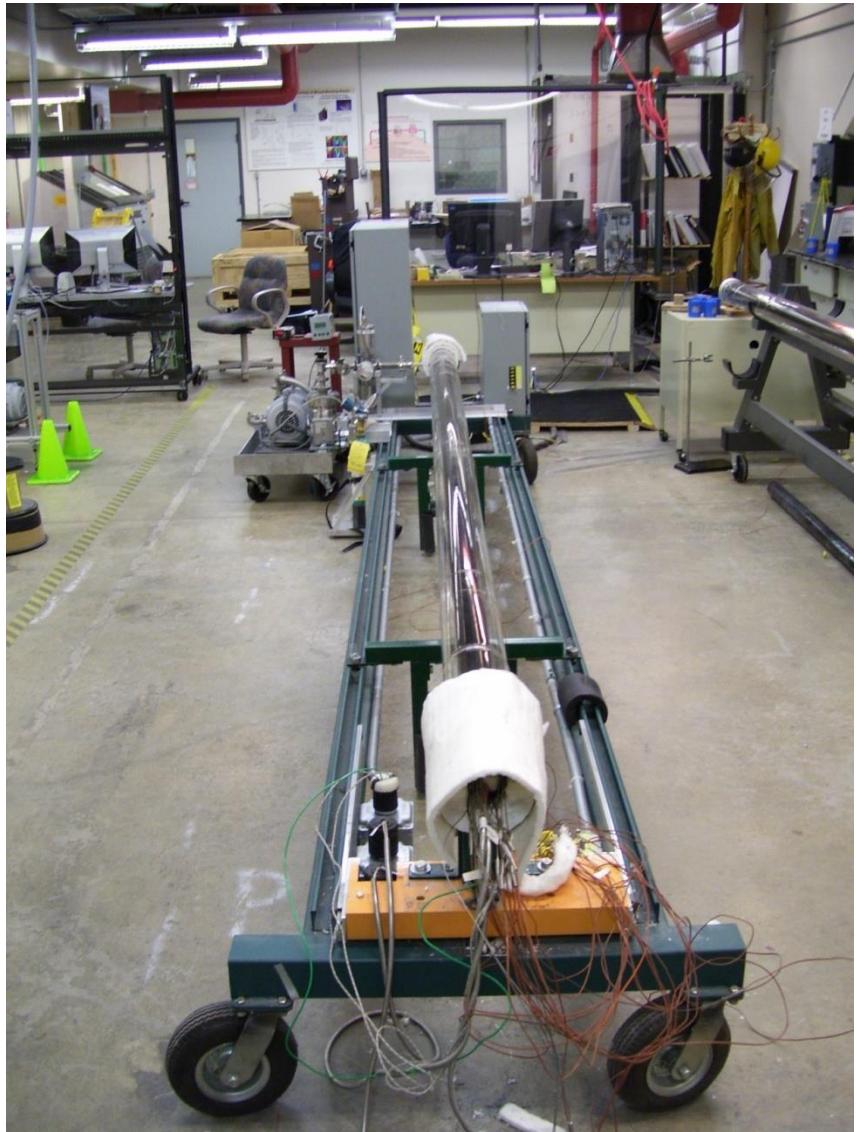
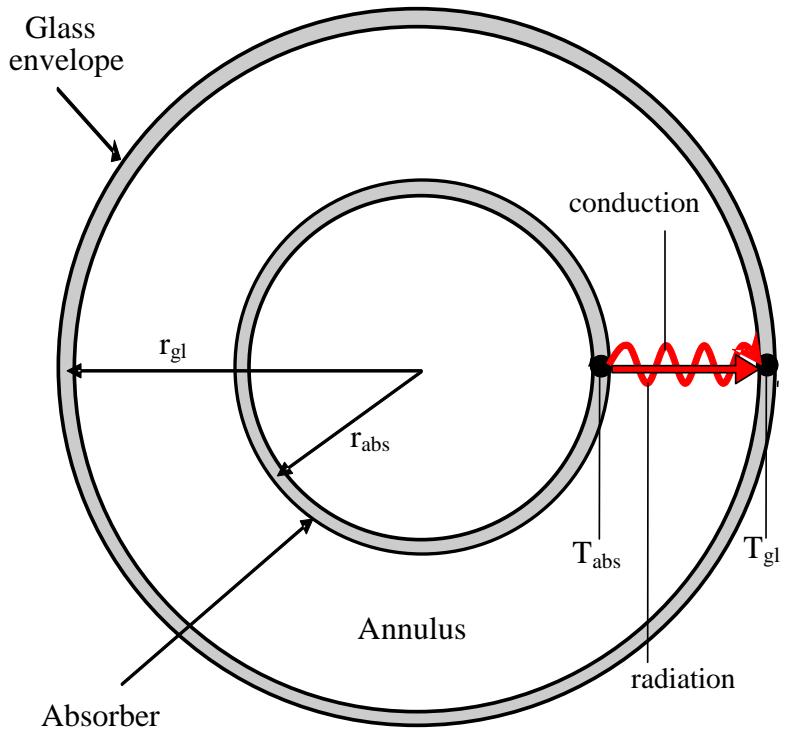


- Background/Motivation 8 slides
- Literature Review 3 slides
- Research Approach 1 slide
- Modeling 11 slides
- Testing 9 slides
- Results 6 slides
- Conclusions 1 slide
- Practical Considerations 2 slides

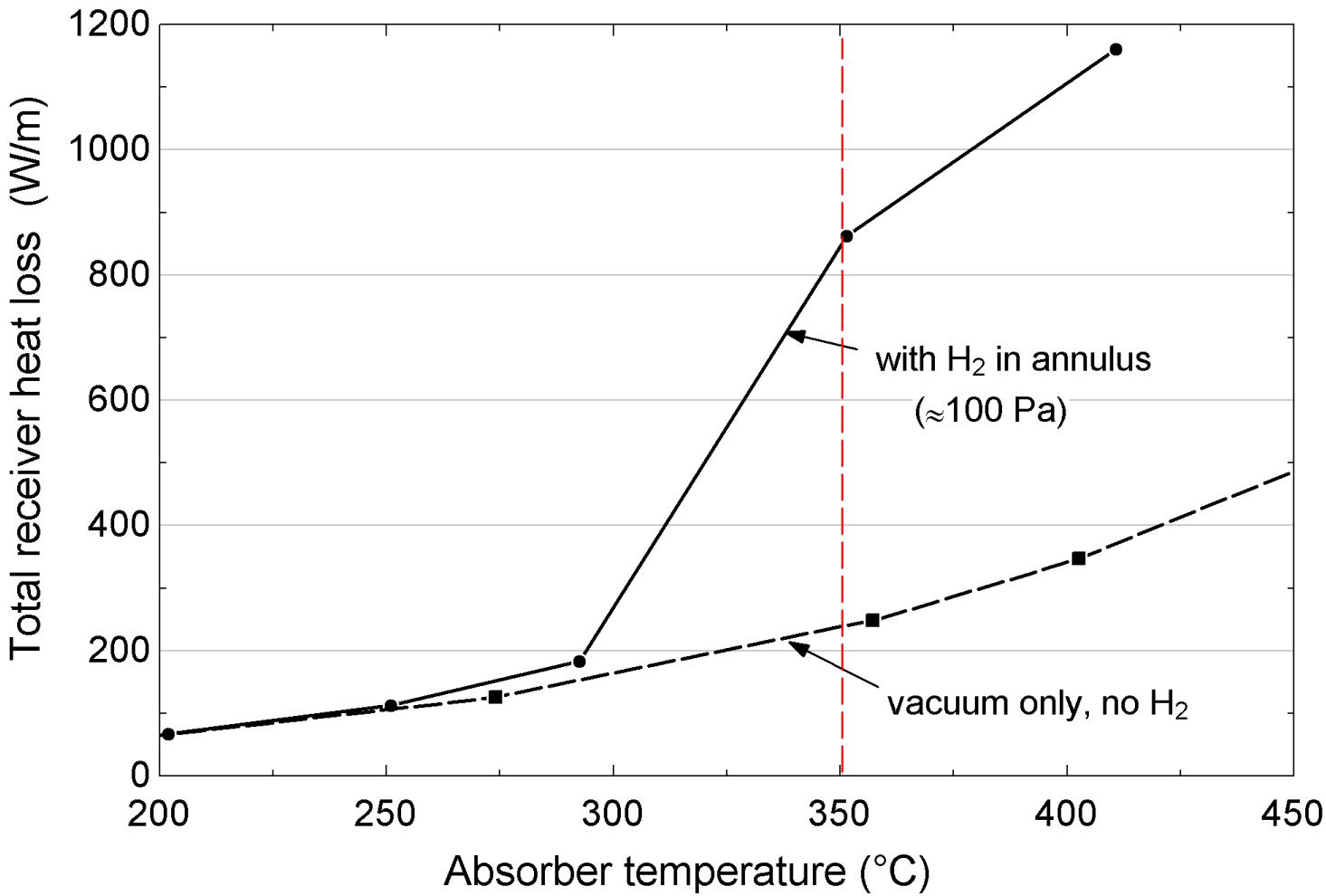
Parabolic Trough Power Plants



Parabolic Trough Receiver



Hydrogen in annulus increases heat loss



Motivation and goal of research



Hydrogen in a receiver annulus increases heat loss from a receiver 2-4x, depending on pressure.

A field of H_2 receivers causes 20% loss of annual revenue in a power plant.

For the time being, the organic oil is the best HTF. Natural, slow degradation generates H_2 .

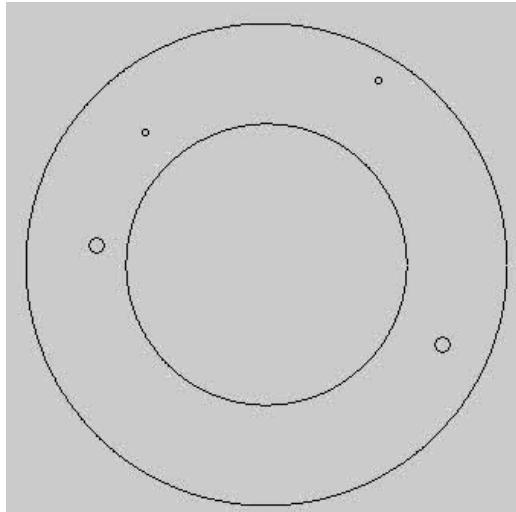
Find a way to live with H_2 permeation into annulus, but decrease its effect on heat conduction by mixing it with slow, massive molecules that don't conduct as much heat.

How much/what gases should be added?

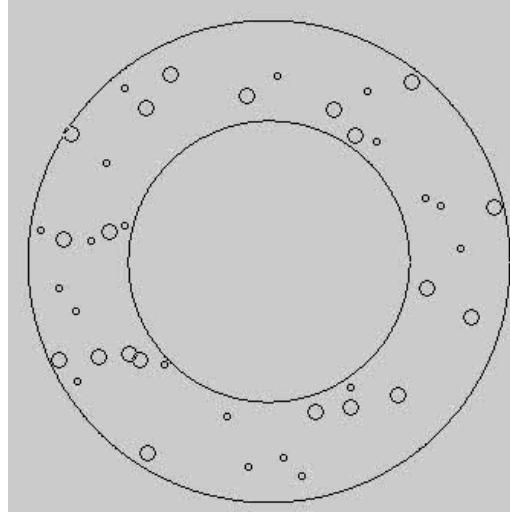
Pressure dependent heat conduction



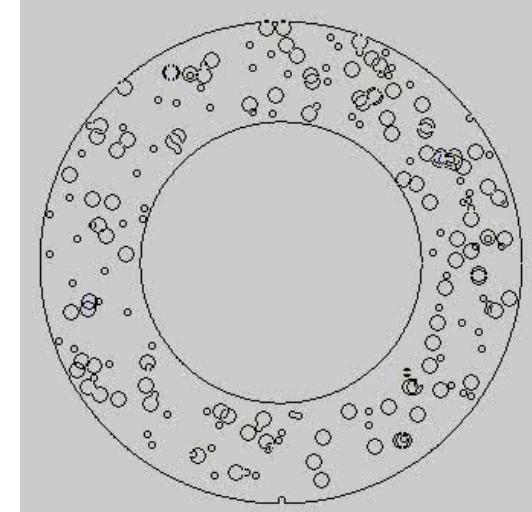
Free molecular



Transition



Continuum



$$q_c \propto P$$

$$q_c = f(\alpha)$$

$$q_c = f(P)$$

$$q_c = f(\alpha)$$

$$q_c \neq f(P)$$

$$q_c \neq f(\alpha)$$

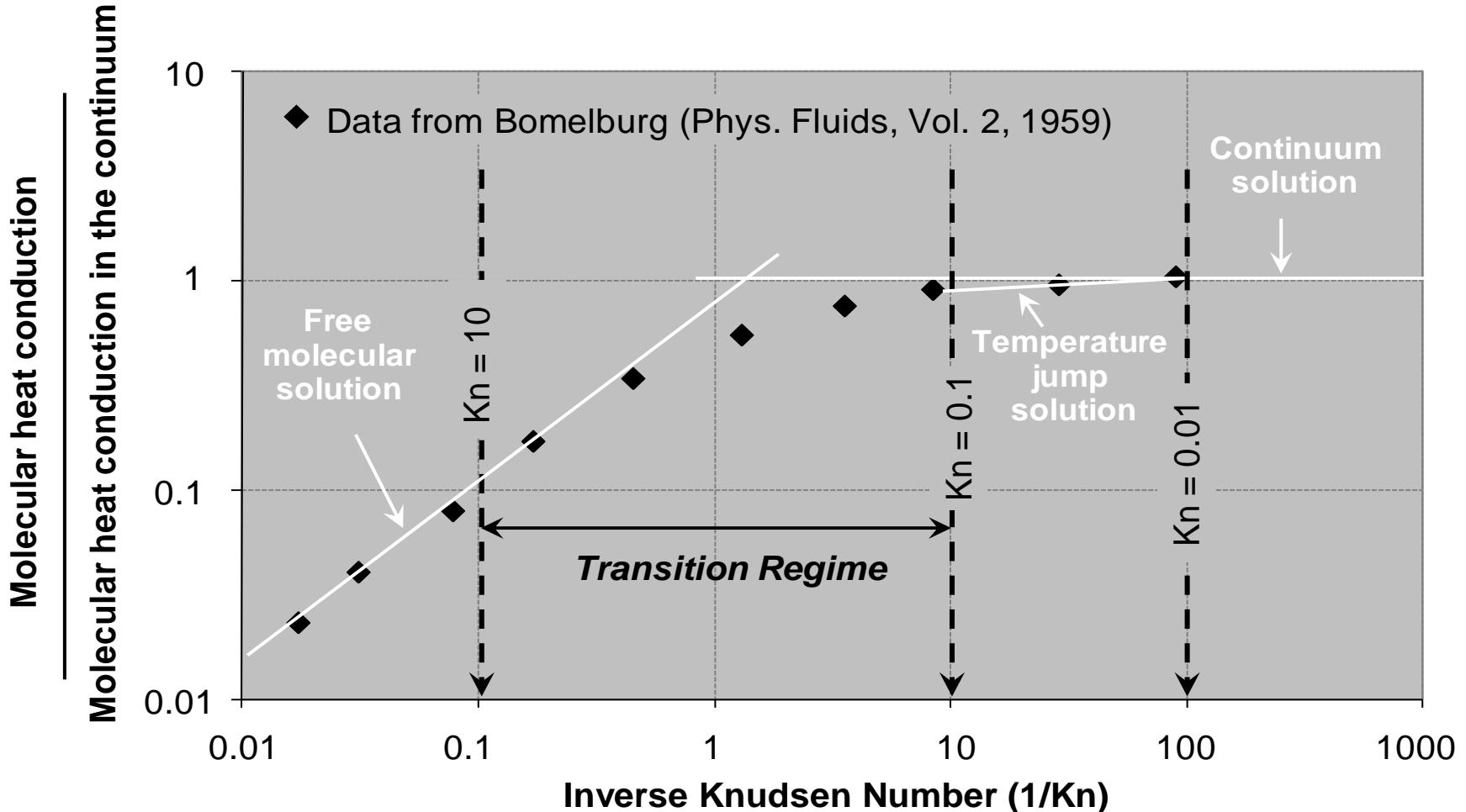
$$\bar{u} = \sqrt{\frac{8\kappa T}{\pi m}}$$

$$\lambda = \frac{1}{\sqrt{2}\pi d^2 n}$$

$$Kn = \frac{\lambda}{L}$$

$$k_\infty = \frac{1}{3} \hat{\rho C_v} \bar{u} \lambda$$

Heat Conduction Regimes



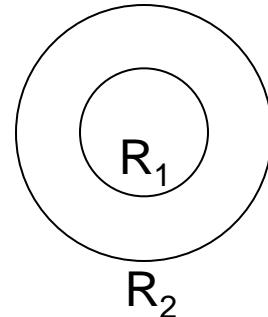
$$Kn = \frac{\lambda}{L}$$

Heat Conduction for Free Molecule and Continuum Regimes



Continuum (molecule-molecule collision dominated, not P dep.)

$$q_{continuum,CC} = \frac{2\pi L k_{mixture}(T_1 - T_2)}{\ln\left(\frac{R_2}{R_1}\right)}$$



Free molecule (wall-molecule collision dominated, P dep.)

$$\frac{q_{FM,CC}}{A_1} = \frac{1}{\frac{1}{\alpha_1} + \left(\frac{R_1}{R_2}\right)\left(\frac{1}{\alpha_2} - 1\right)} \times \frac{P\left(C_v + \frac{R_{gas}}{2}\right)}{\left(2\pi M R_{gas} T_{avg}\right)^{1/2}} \times (T_1 - T_2)$$

$$q_{FM,Mixture} = q_{FM,Gas1} + q_{FM,Gas2}$$

Transition Regime (a mixture of the two)

Solve the Boltzmann Transport equation



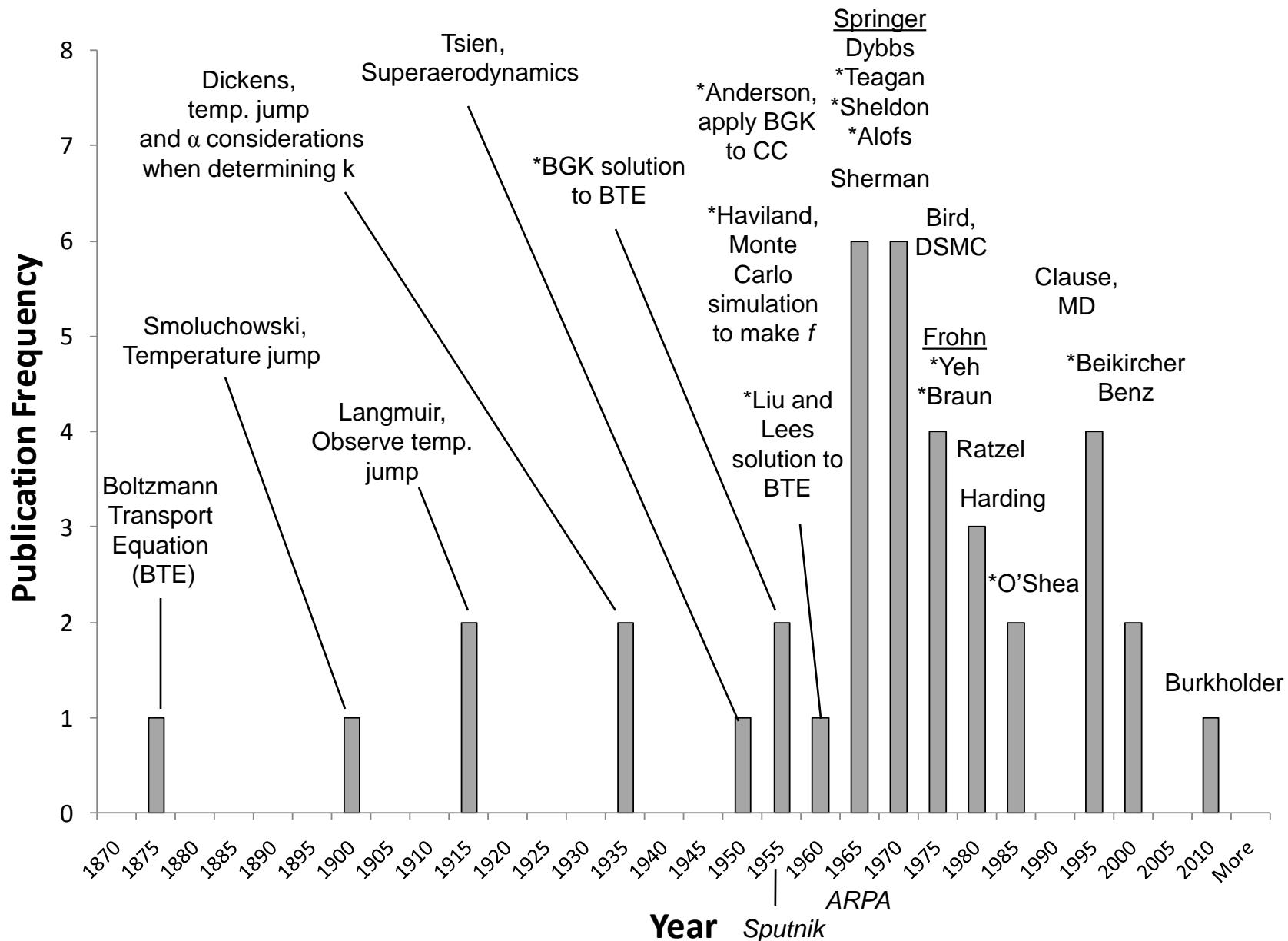
The Boltzmann Transport Equation

$$f = f(t, \mathbf{x}, \mathbf{v})$$

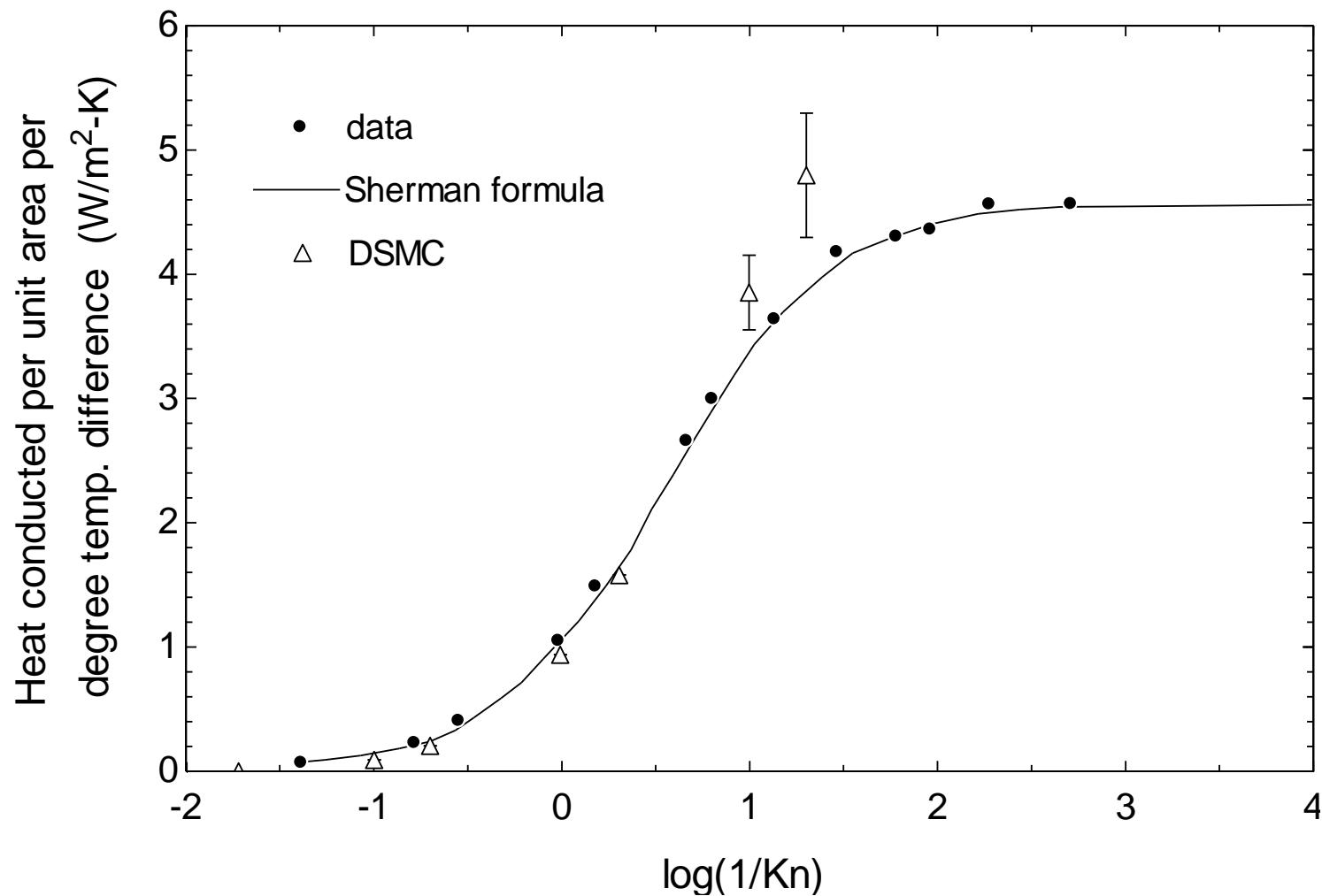
$$\frac{\partial f}{\partial t} + \mathbf{v} \frac{\partial f}{\partial \mathbf{x}} + \mathbf{a} \frac{\partial f}{\partial \mathbf{v}} = \int (f' f_1' - f f_1) g b db d\varepsilon d\mathbf{v}_1$$

$f(t, \mathbf{x}, \mathbf{v}) d\mathbf{x} d\mathbf{v}$ = the probable number of molecules in the element of physical volume $d\mathbf{x}$ near the point \mathbf{x} at time t , with velocities in the element $d\mathbf{v}$ near \mathbf{v}

Literature Review



O'Shea and Collins, 1991. *An Experimental Study of Conduction Heat Transfer in Rarefied Polyatomic Gases*



Literature review summary



Modeling methods that show promise: Liu – Lees Moment Method, Sherman Interpolation Formula, DSMC

Will they work in this case?

Geometry	Ratio of outer radius to inner radius (Ro/Ri)	Gases in annulus	Knudsen number range	Temperature difference, $T_{\text{hot}}/T_{\text{cold}} - 1$	Accommodation coefficient on the hot surface	Accommodation coefficient on the cold surface
Concentric Cylinder	1.7	pure species: Ar, Xe, H ₂ ----- mixtures: Ar-H ₂ , Xe-H ₂	2e-5 - 50	$\Delta T:$ 200 - 300°C ----- 0.5 – 0.9 (ratio from temperatures in Kelvin)	0.3 - 1	0.3 - 1

No comparable data in literature to check them against.

Research Approach



Test and predict heat conduction in a parabolic trough receiver:

Gases	Pure gases: H ₂ , Ar, Xe Mixtures: H ₂ /Ar, H ₂ /Xe
Gas molar fractions	Pure gases: 1.0 H ₂ 1.0 Ar 1.0 Xe Mixtures: 0.50 H ₂ /0.50 Ar 0.25 H ₂ /0.75 Ar 0.10 H ₂ /0.90 Ar 0.525 H ₂ /0.475 Xe 0.272 H ₂ /0.728 Xe 0.118 H ₂ /0.882 Xe
Absorber temperature	350°C
Glass temperature	60-150°C depending on gas composition and pressure
Test pressure range	0.1 – 10,000 Pa
Simulation models	Sherman interpolation formula Direct Simulation Monte Carlo method (DSMC)

Modeling – Sherman interpolation formula



Sherman interpolation formula:

$$\frac{1}{q} = \frac{1}{q_{FM,1}} + \frac{1}{q_{\infty}}$$

$$q_{FM,1} = \frac{1}{\frac{1}{\alpha_{1,1}} + \frac{R_1}{R_2} \left(\frac{1}{\alpha_{1,2}} - 1 \right)} \cdot \frac{P_1 \left(C_{v,1} + \frac{R_g}{2} \right)}{\left(2\pi M_1 R_g T_{avg} \right)^{1/2}} \cdot (T_1 - T_2) \cdot 2\pi R_1$$

$$q_{FM,2} = \frac{1}{\frac{1}{\alpha_{2,1}} + \frac{R_1}{R_2} \left(\frac{1}{\alpha_{2,2}} - 1 \right)} \cdot \frac{P_2 \left(C_{v,2} + \frac{R_g}{2} \right)}{\left(2\pi M_2 R_g T_{avg} \right)^{1/2}} \cdot (T_1 - T_2) \cdot 2\pi R_1$$

$$q_{\infty} = \frac{2\pi k_{mixture} (T_1 - T_2)}{\ln \left(\frac{R_2}{R_1} \right)}$$

$k \pm 2\%$ pure gases, $\pm 10\%$ gas mixture with H₂
 $\alpha \pm 25\%$

Accommodation coefficients



Song and Yovanovich (1987) correlation

$$\alpha = \exp\left[C_0\left(\frac{T_s - T_0}{T_0}\right)\right]\left(\frac{M_g^*}{C_1 + M_g^*}\right) + \left\{1 - \exp\left[C_0\left(\frac{T_s - T_0}{T_0}\right)\right]\right\}\left\{\frac{2.4\mu}{(1+\mu)^2}\right\}$$

where

M_g^* is the molar mass for monatomic gases, 1.4 times the molar mass for diatomic/polyatomic gases

C_0 is -0.57, dimensionless

C_1 is 6.8 (g/mole)

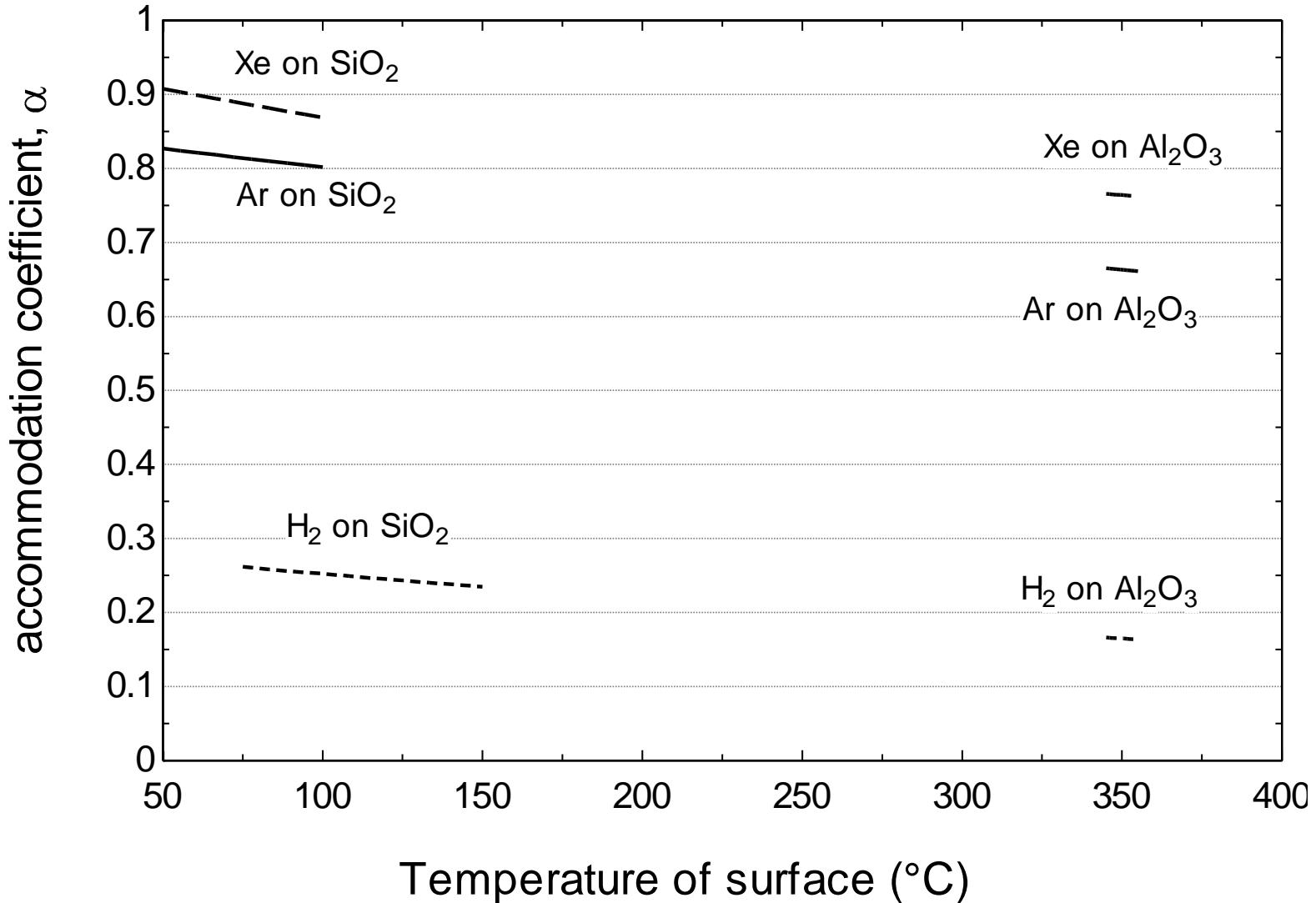
$\mu = \frac{M_g}{M_s}$ = ratio of molar mass of gas to the molar mass of the surface

$T_0 = 273$ K

Accommodation coefficients



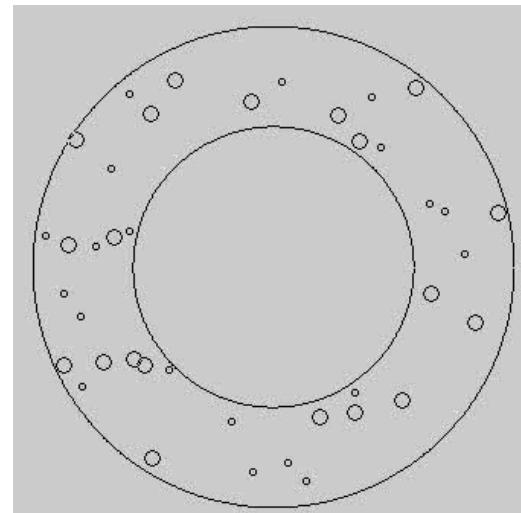
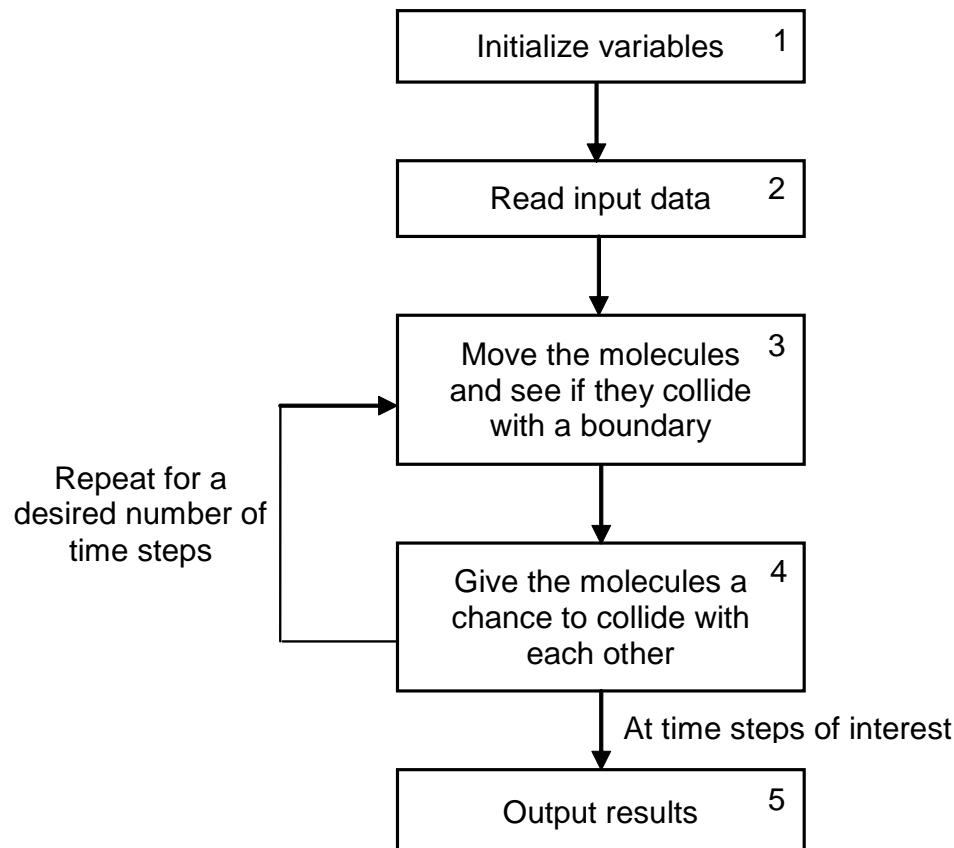
Correlation results:



Modeling - Direct Simulation Monte Carlo Method



“DSMC is a technique for the computer modeling of a real gas flow by several thousand simulated molecules. The velocity components and position coordinates of the simulated molecules are stored in the computer and these are modified with time as the molecules are concurrently followed through representative collisions and boundary interactions...” – G.A. Bird, 1970



DSMC details



Movement – deterministic particle kinematics: $\mathbf{x} = \mathbf{x}_0 + \mathbf{v}_0 \Delta t$

If movement leads to impact with a boundary:

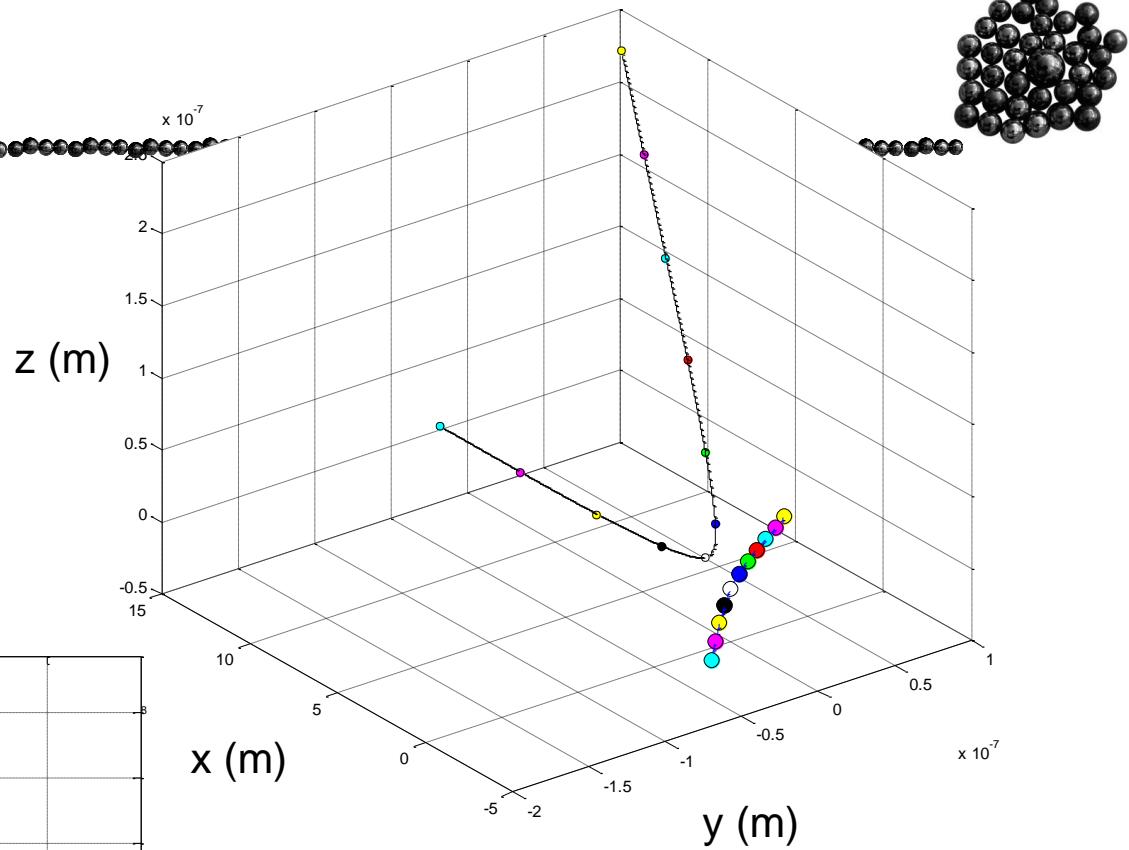
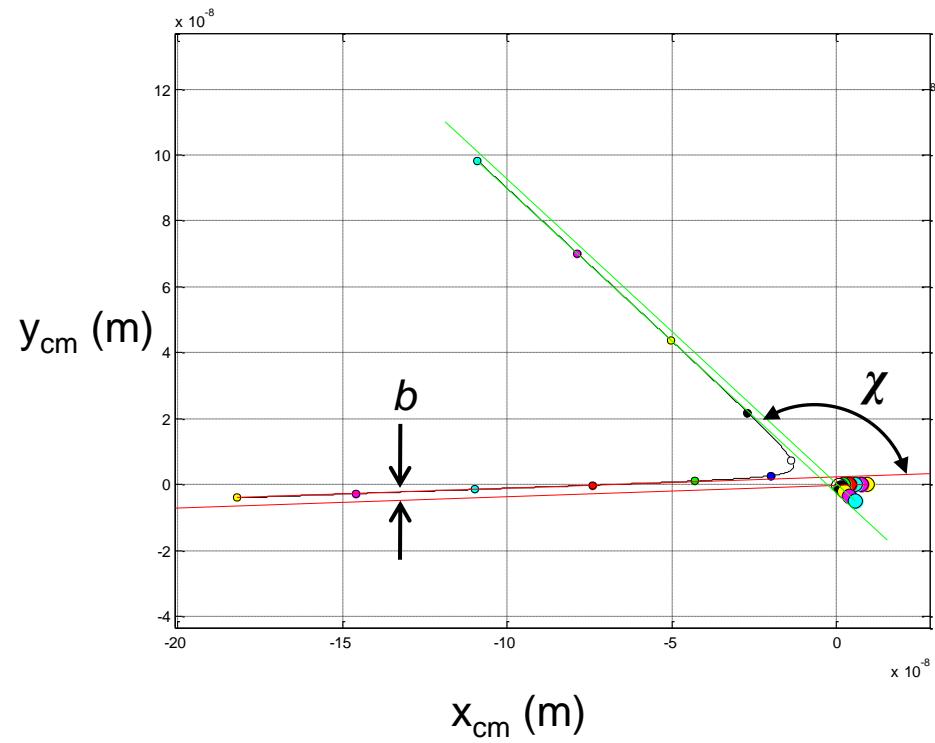
compare R_f to α , if $R_f > \alpha$ specular reflection, otherwise diffuse reflection

After the movement step, two adjacent molecules selected randomly. Do they collide?

$$P = \frac{F_N \sigma_T c_r \Delta t}{V_C} \quad \Rightarrow \quad P = \frac{(\sigma_T c_r)}{(\sigma_T c_r)_{\max}} \quad \text{if } R_f < P \text{ a collision occurs}$$

Molecular collisions

Three dimensional collisions are planar in the center-of-mass frame of reference and simplify to a distance of closest approach, b , and the deflection angle, χ



$$\cos(\chi) = 2R_f^{1/\alpha_s} - 1$$

DSMC inputs



DSMC input	Hydrogen	Argon	Xenon	Uncertainty estimate
Molecular diameter (m)	2.88e-10	4.11e-10	5.65e-10	0.5%
Diameter reference temperature (K)	273	273	273	-
Viscosity temperature index (-)	0.67	0.81	0.85	±1%
Reciprocal of scattering coefficient (-)	0.7407	0.7143	0.6944	±3.5%
Mass of one molecule (kg)	3.44e-27	66.3e-27	218e-27	-
Rotational degrees of freedom (-)	2	0	0	-
Rotational relaxation number (-)	5	0	0	±40%
Accommodation on absorber	0.34	0.66	0.76	±25%
Accommodation on glass	0.25	0.82	0.90	±25%

DSMC Discretization Study



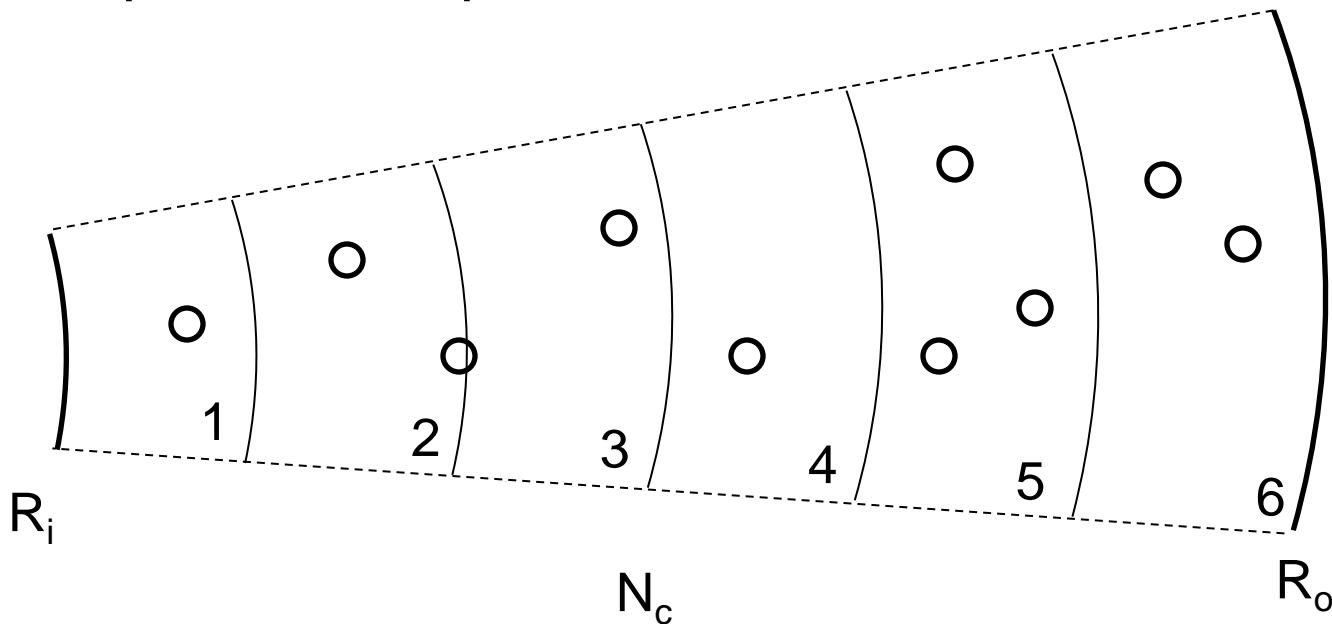
Number of cells, N_c ?

Number of molecules, N_m ?

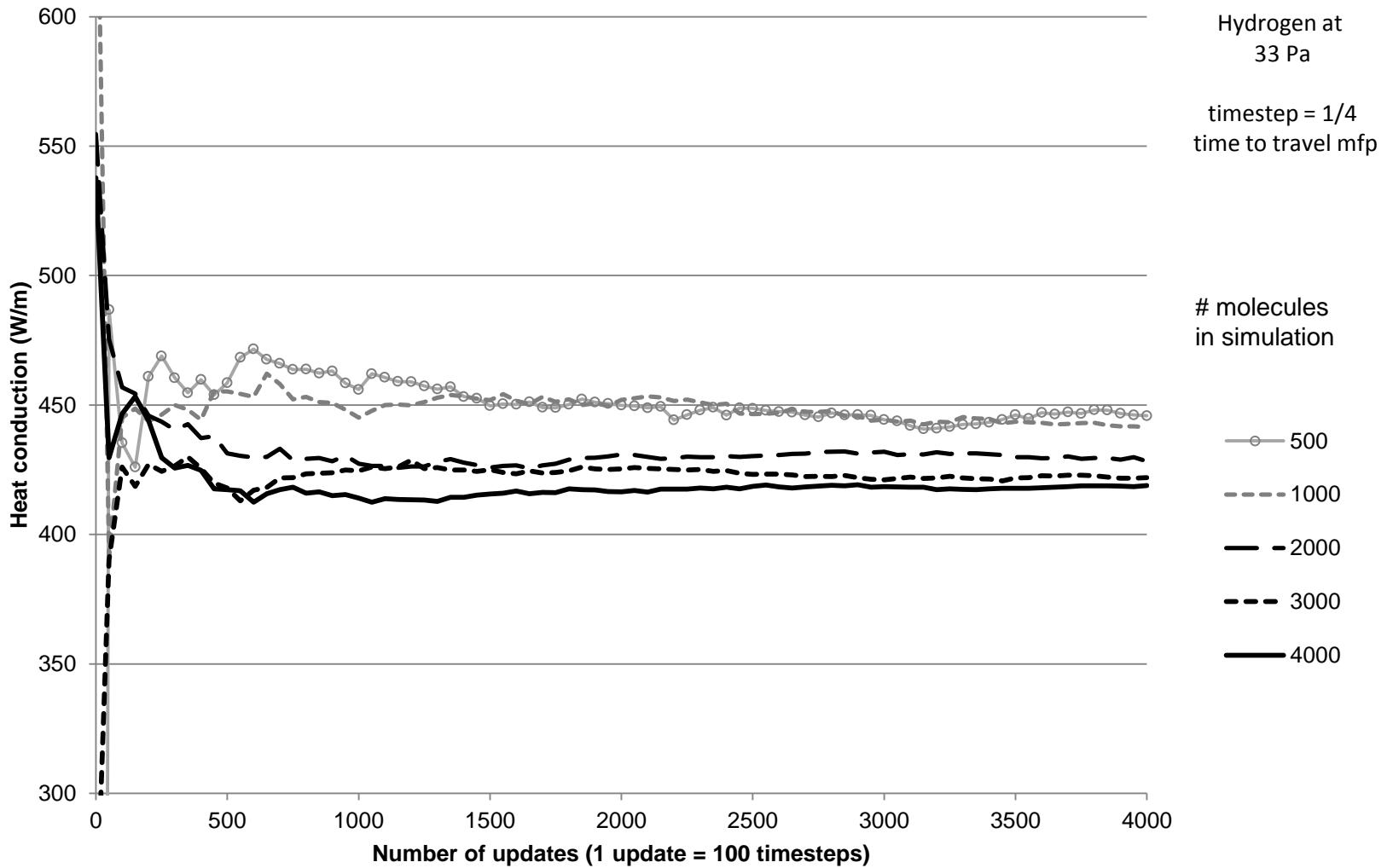
Time step, Δt ?

When is steady state reached?

Answers pressure dependent?

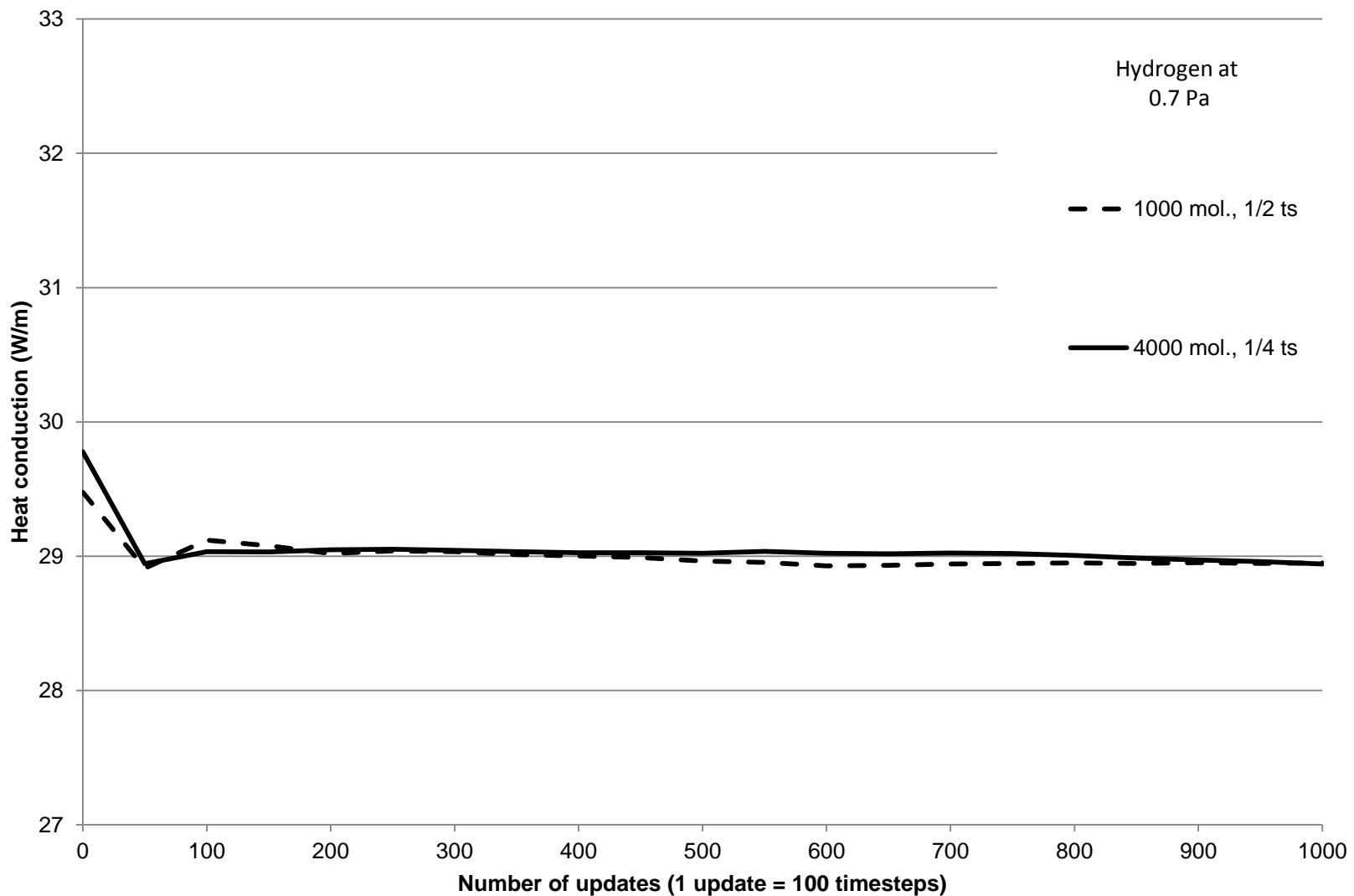


Number of molecules – 33 Pa





Number of molecules and time step – 0.7 Pa



Discretization study results



Number of cells, $N_c = 20$, 400 subcells

Number of molecules, $N_m = 3000$

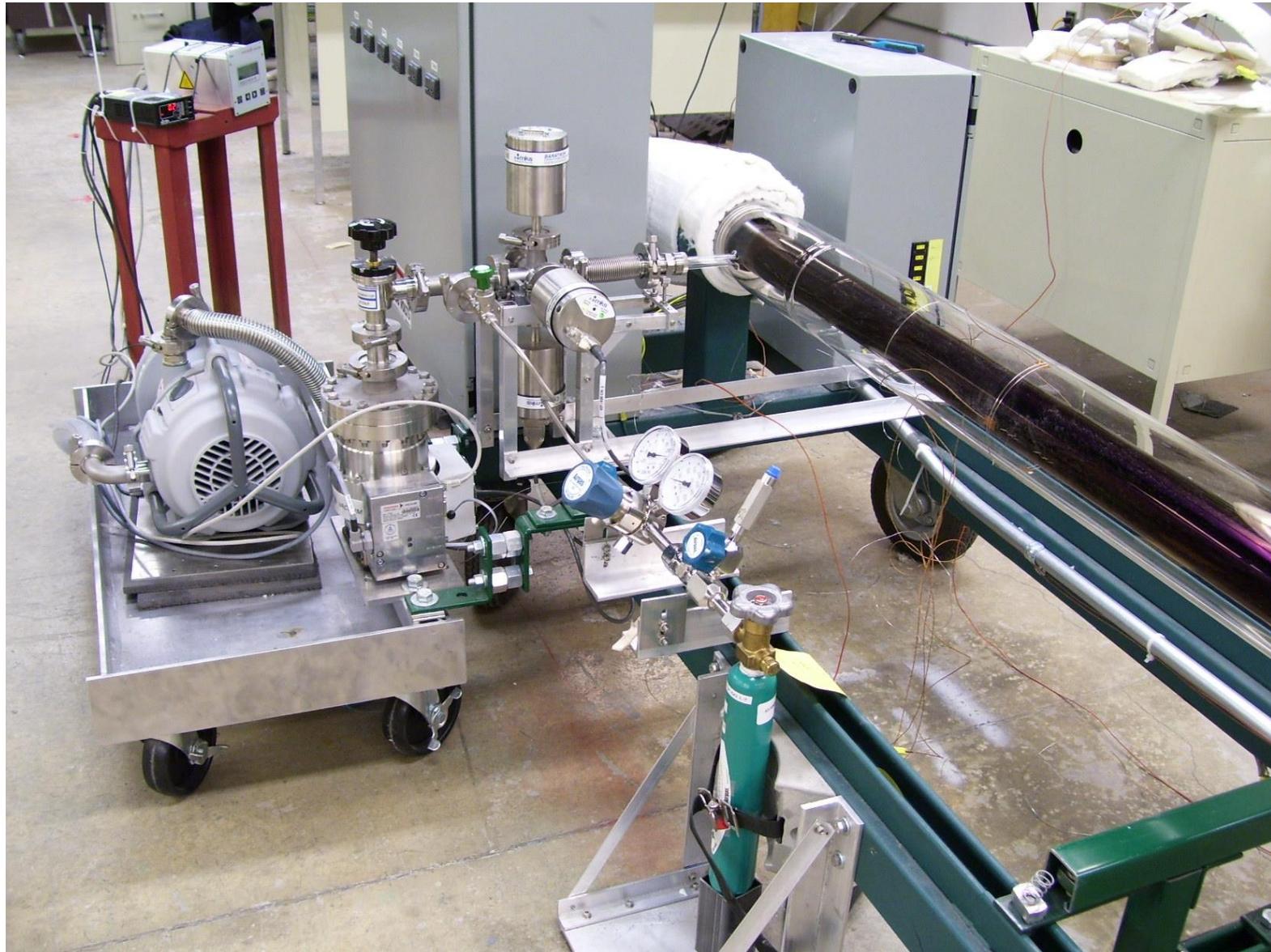
Time step, $\Delta t = \frac{1}{2}$ mean collision time calculated at each pressure

Steady state reached between 10,000 and 100,000 time steps, depending on pressure

Expect good results through 30 Pa (temp. jump regime)



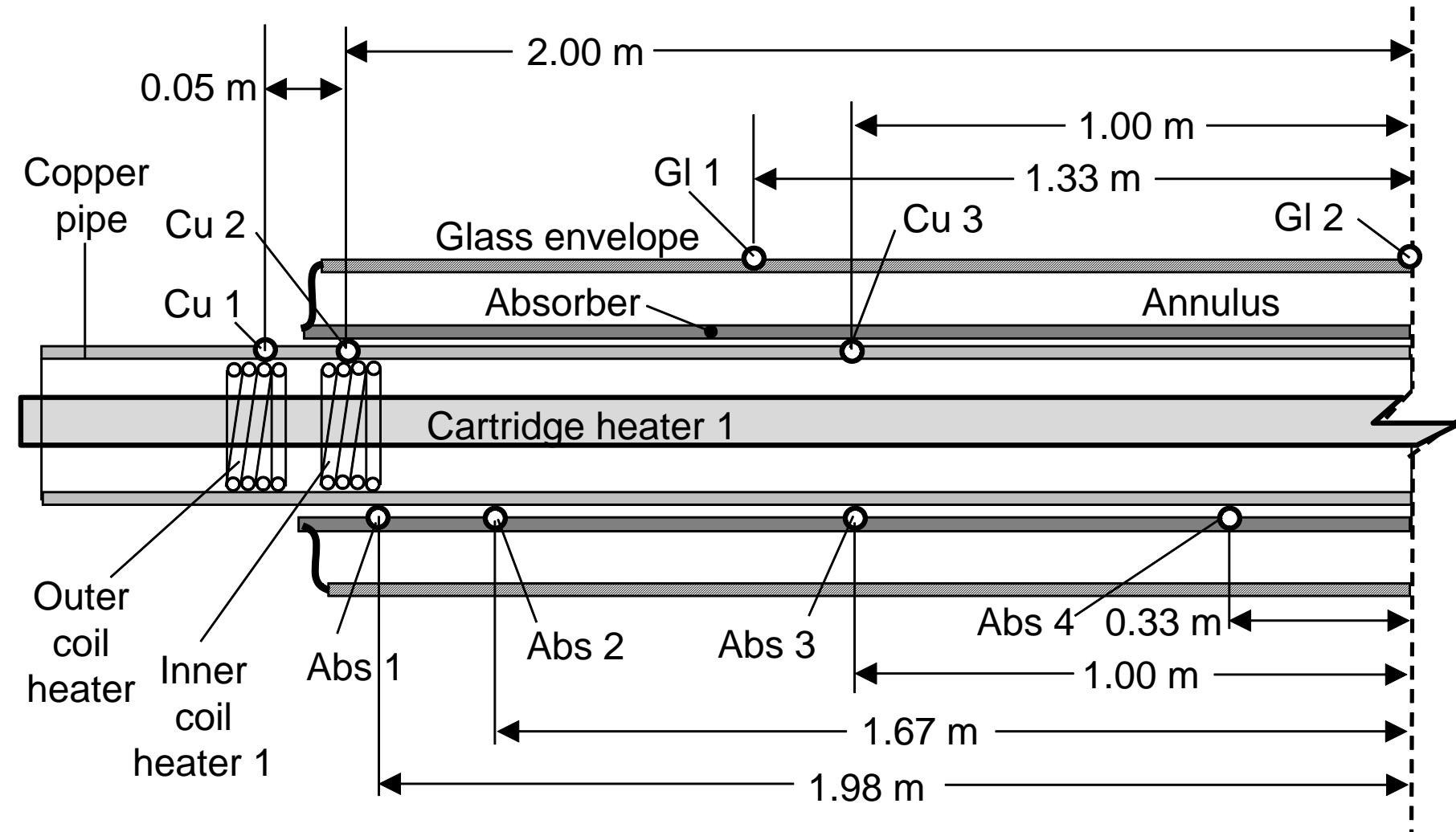
Testing



Schematic

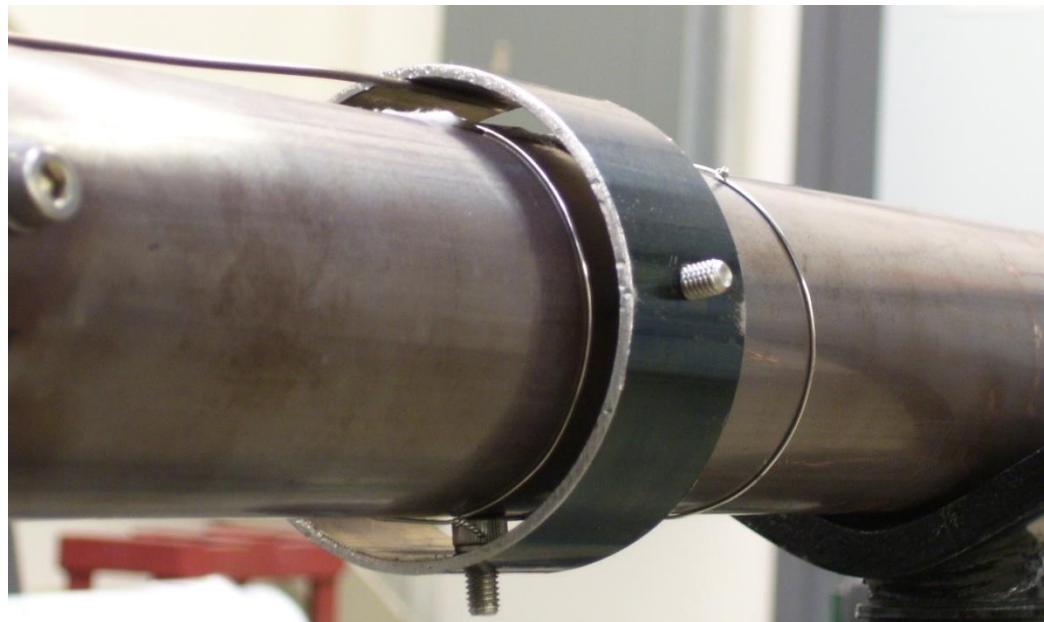
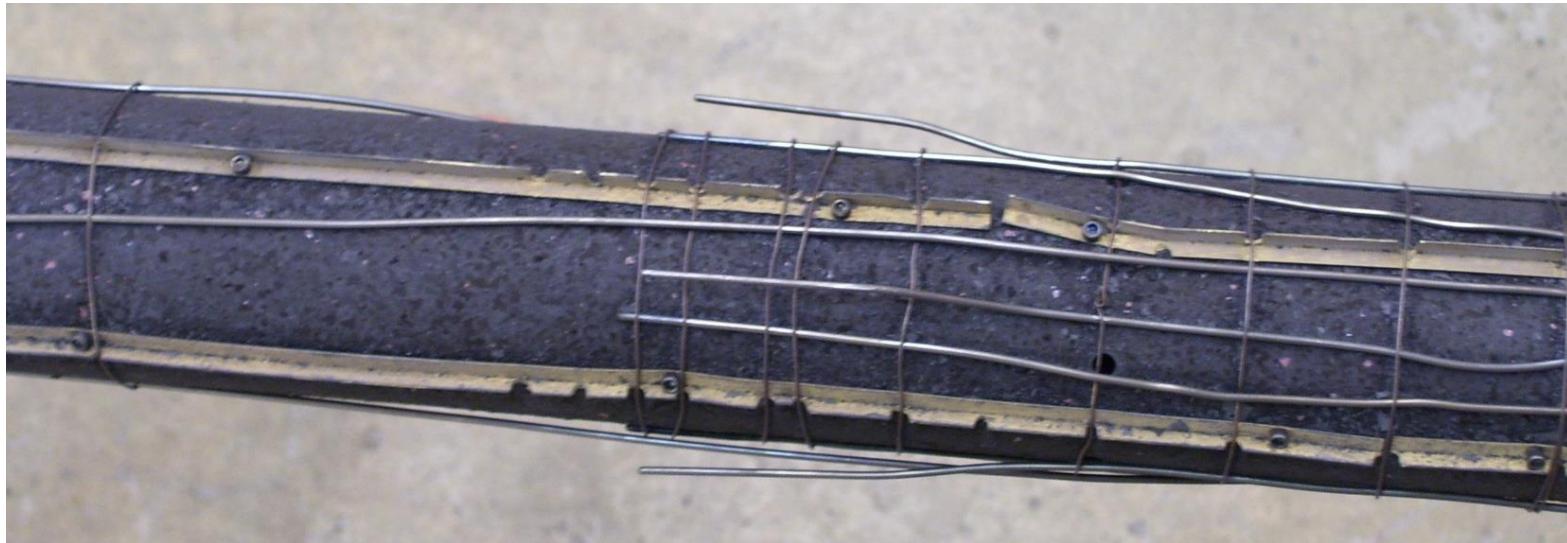


Receiver
Center



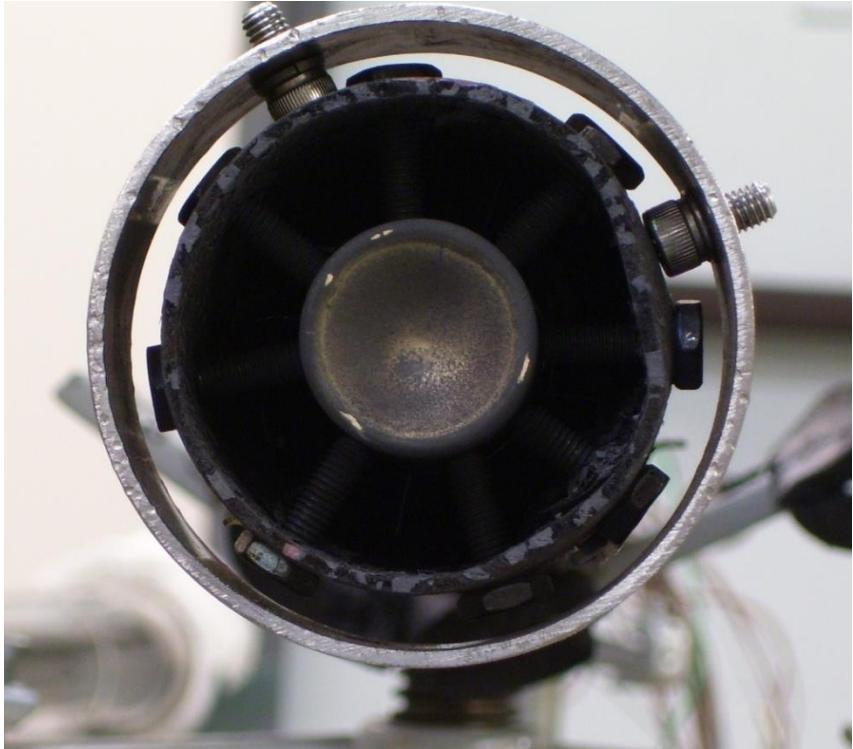


Absorber temperature measurement

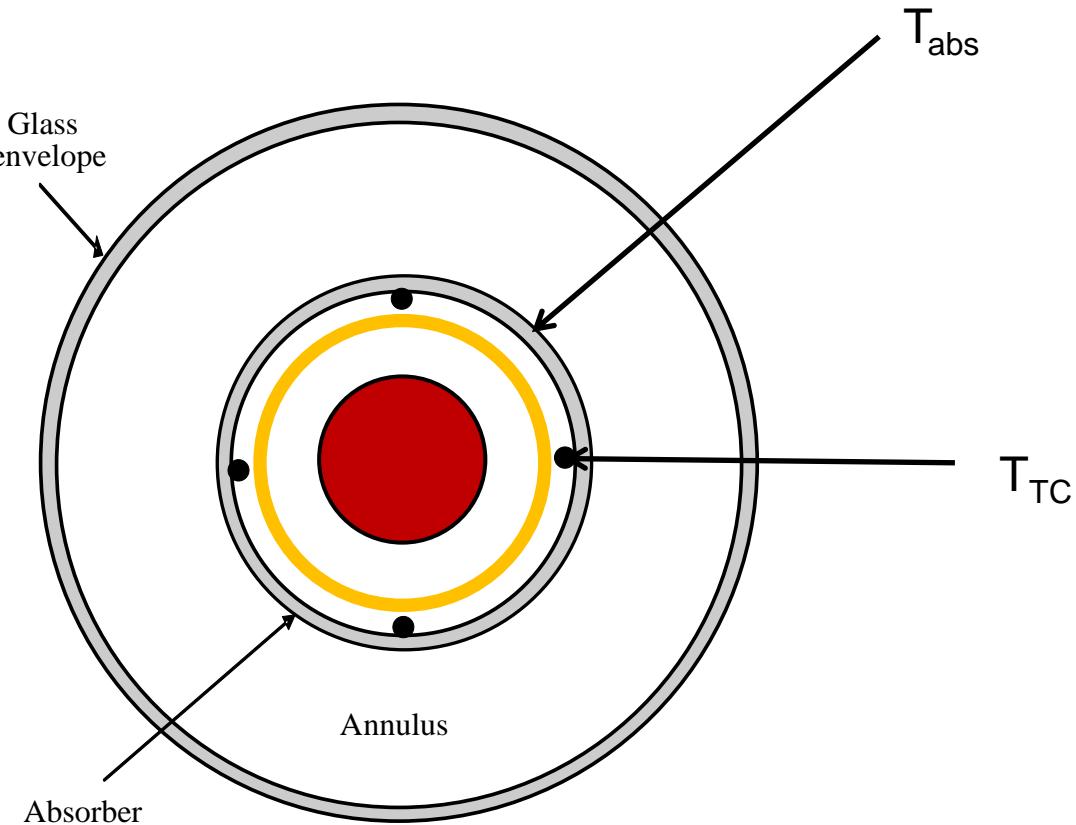




Circumferential temperature uniformity



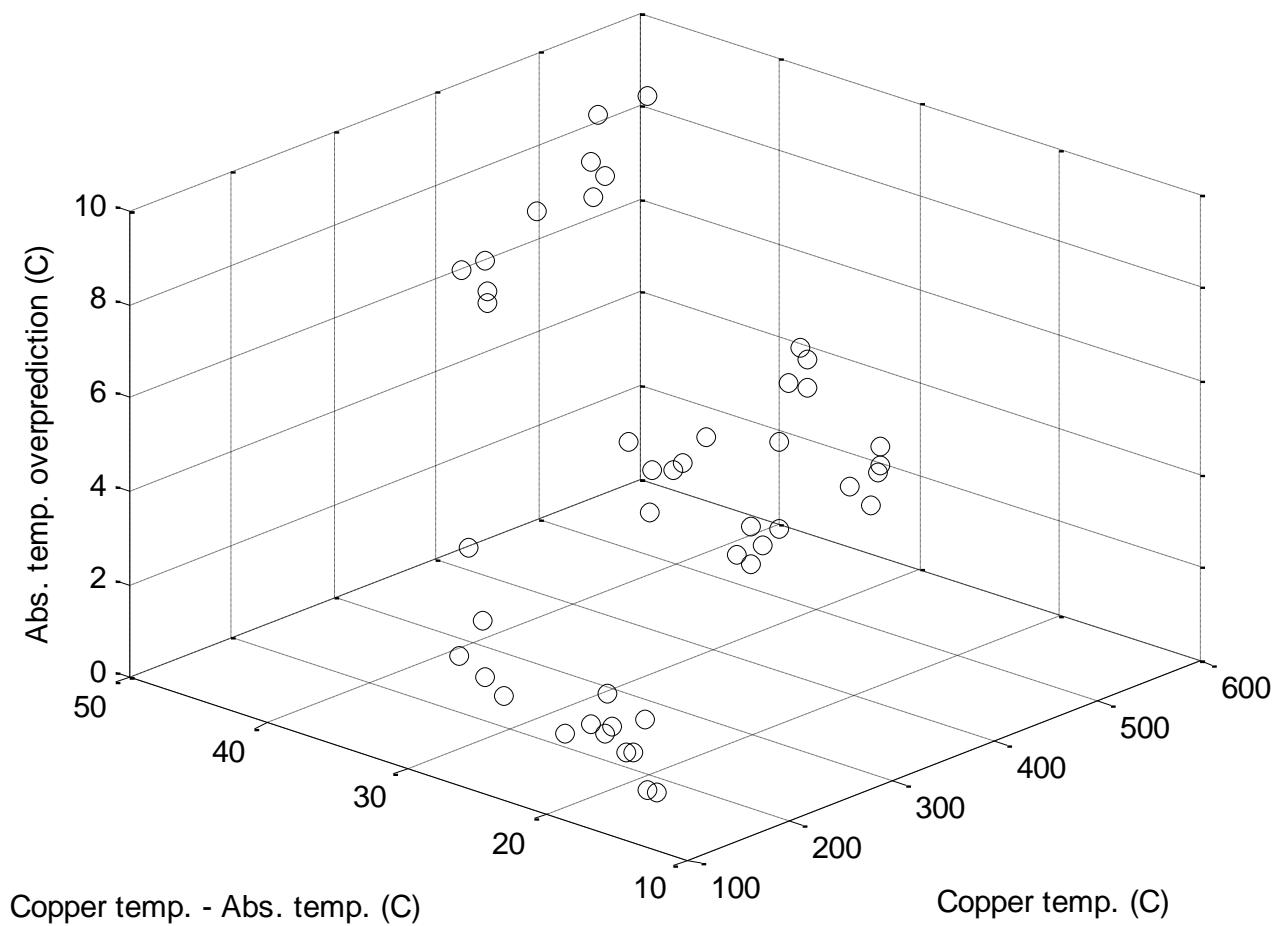
Correcting for TC heating



$$T_{TC} \neq T_{abs}$$

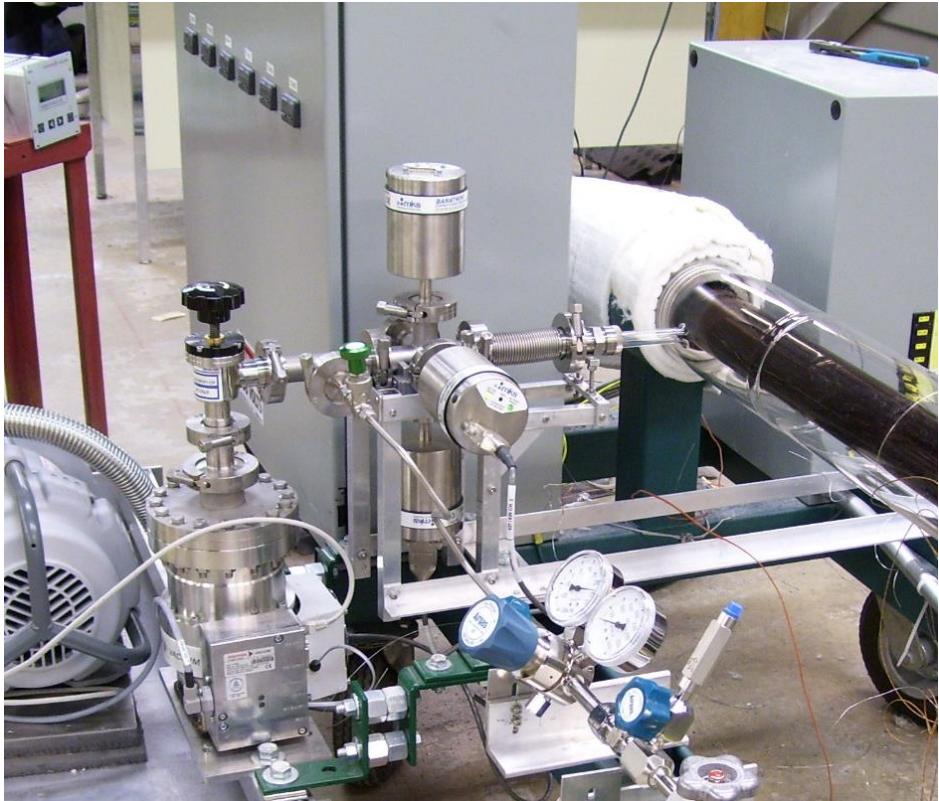
$$T_{TC} > T_{abs}$$

Absorber temp. over-prediction test results



$$O_p = -2.1825 + 0.0042 \cdot T_{Cu} + 0.1575 \cdot \Delta T$$

Power measurement, pressure measurement





Data acquisition





Safe Operating Procedure for:
Receiver Hydrogen Permeation Testing
And
Receiver Heat Loss Testing with Hydrogen/Inert Gas Mixtures

Emergency Shutdown Procedures:

In case of an emergency, there are two large disconnect switches. One is on the east wall labeled with a large sign "Main Power HCE Receiver Test Stand #1 Disconnect" and the second is on the west wall labeled "Test Stand #2 Receiver Hydrogen Permeation Test Emergency Shutoff." Turning off the power will de-energize the system for the indicated test stand. The data acquisition systems are powered by UPS on the floor near the desk and should be left on to monitor the system until the outer temperature glass temperature is below 50°C.

SIGNATURES

Concurrence:

Frank Burkholder, Principal Author

Date _____

Greg Glatzmaier, Author

Date _____

Chuck Kutscher, Line Manager

Date _____

Maureen Jordan, EHS Office Director

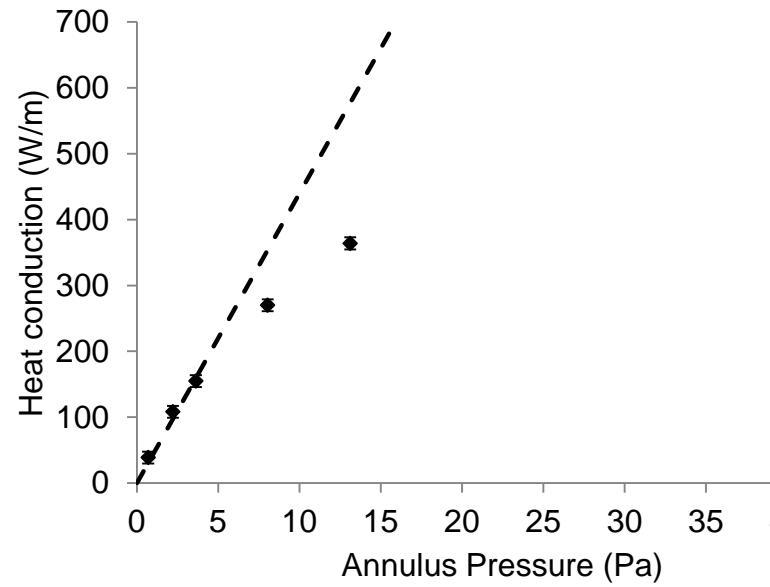
Date _____

Approval:

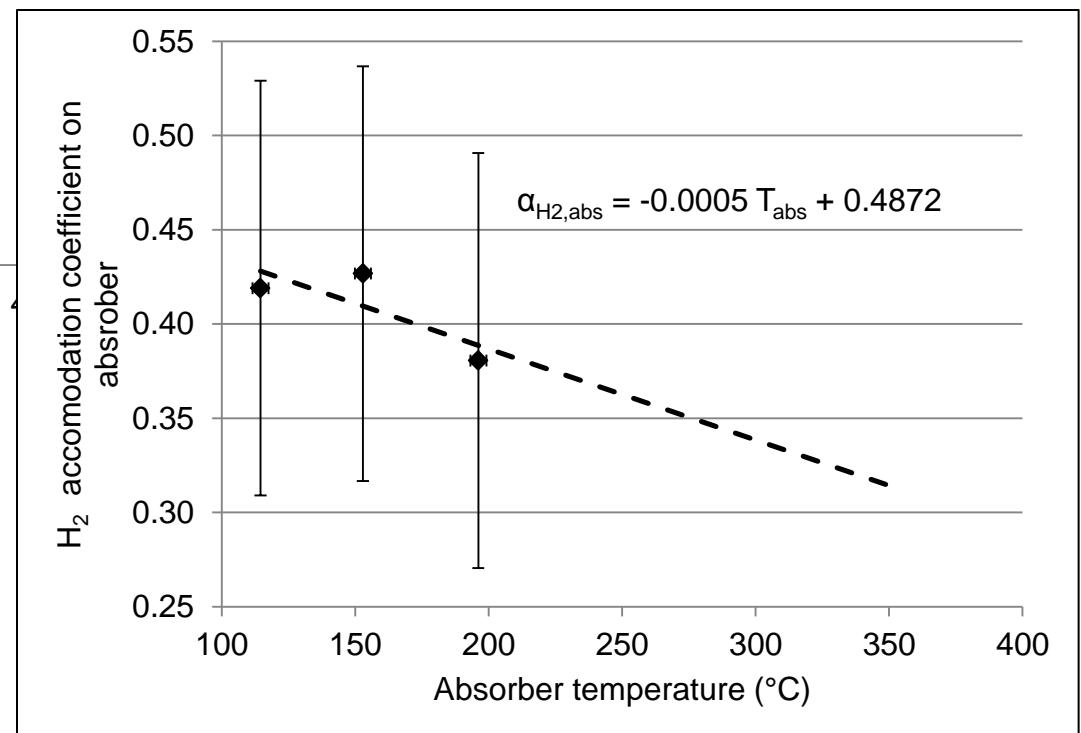
Dave Mooney, 5500 Center Director

Date _____

Results – H₂ accommodation coefficient on absorber

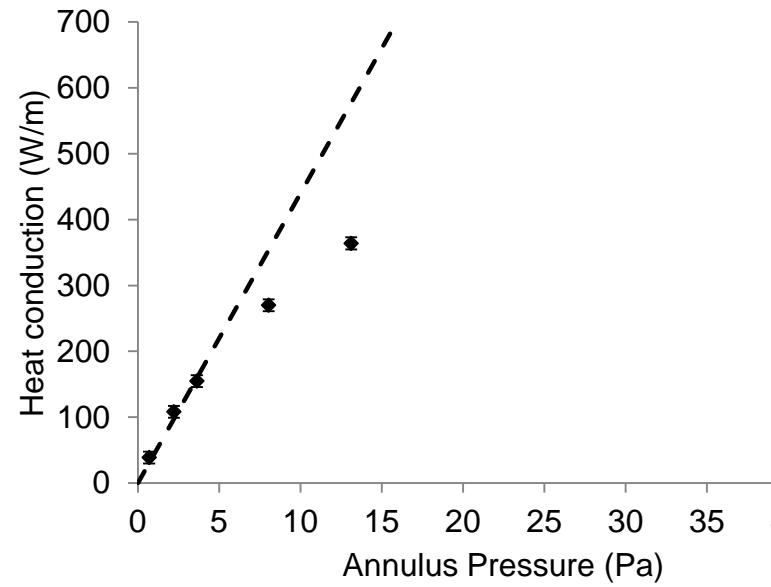


Free molecule tests
 $\alpha = 0.34 \pm 23\%$

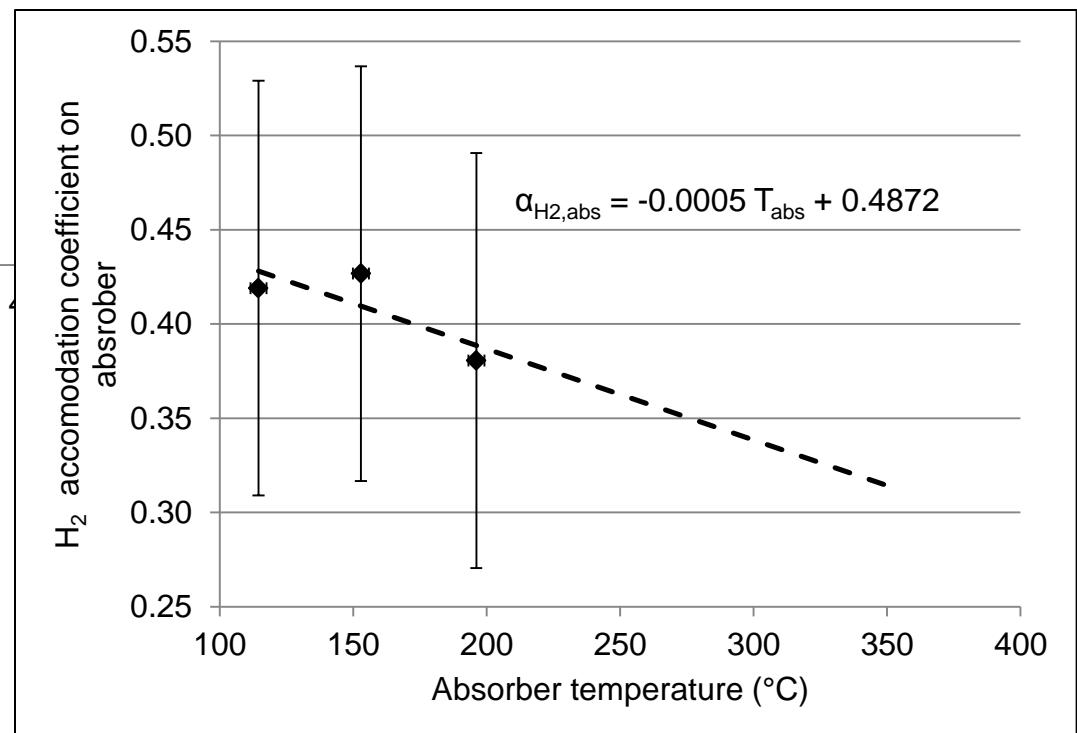


Temperature jump tests
 $\alpha = 0.31 \pm 33\%$

Results – H₂ accommodation coefficient on absorber

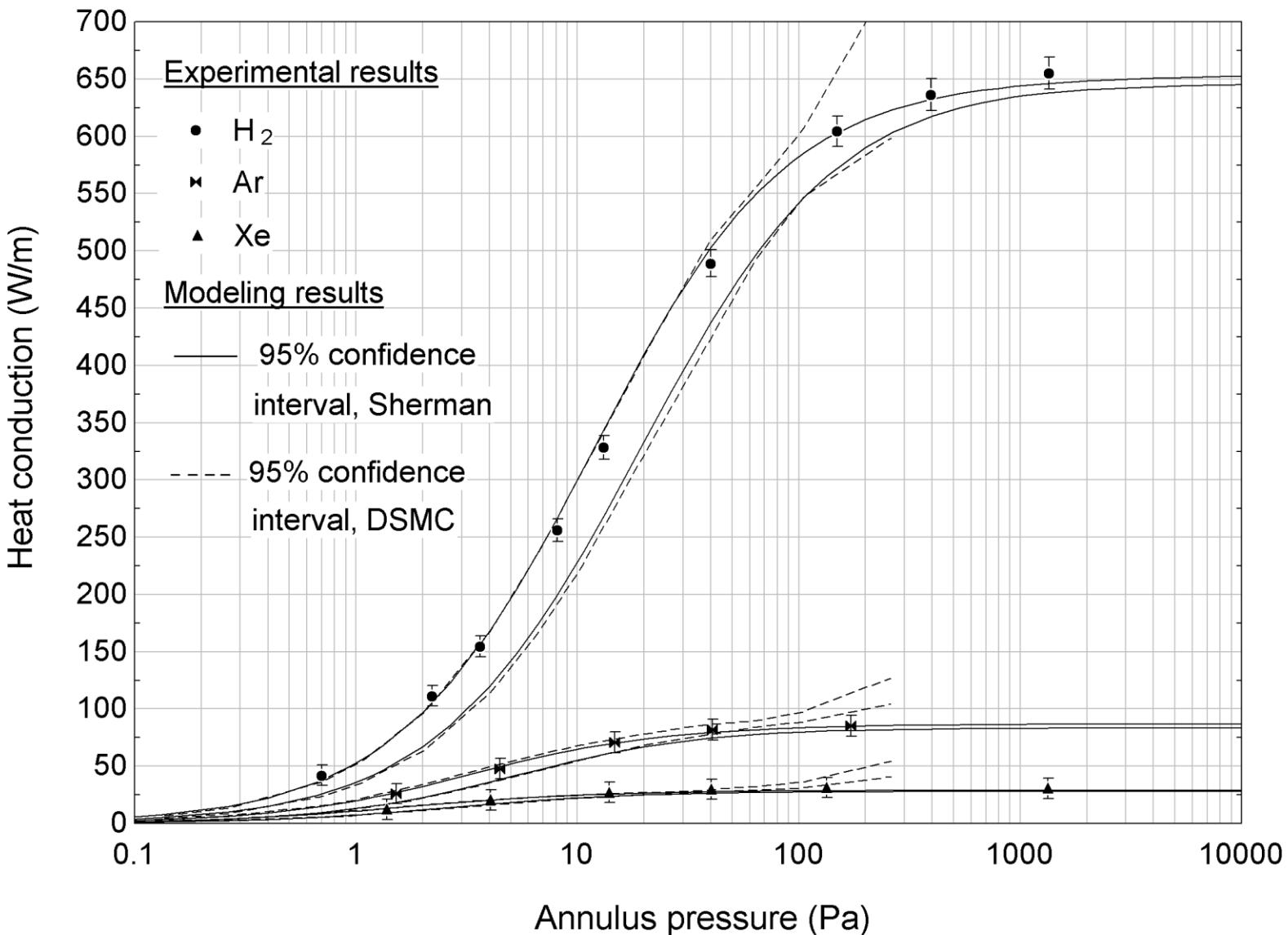


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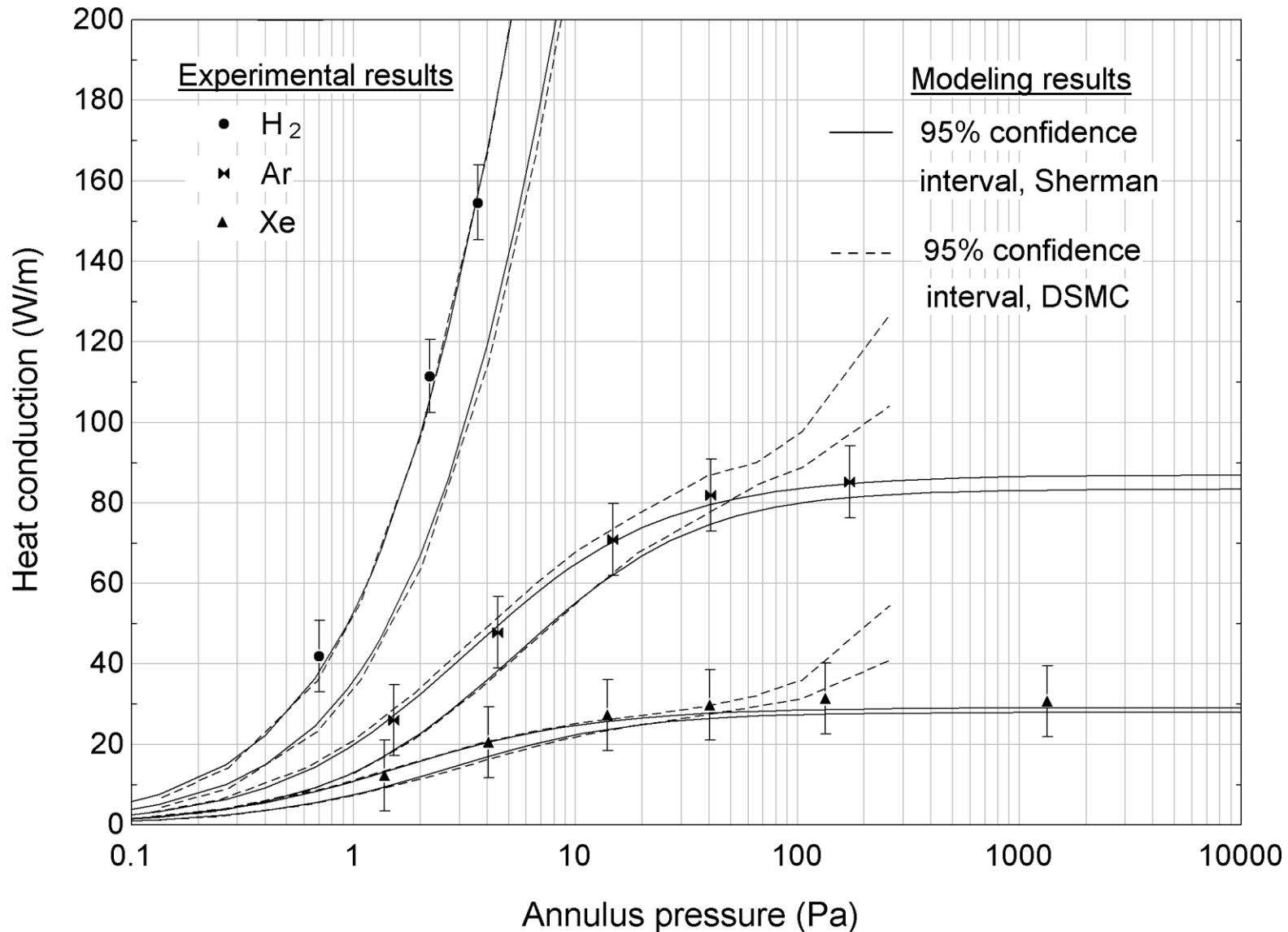


Temperature jump tests
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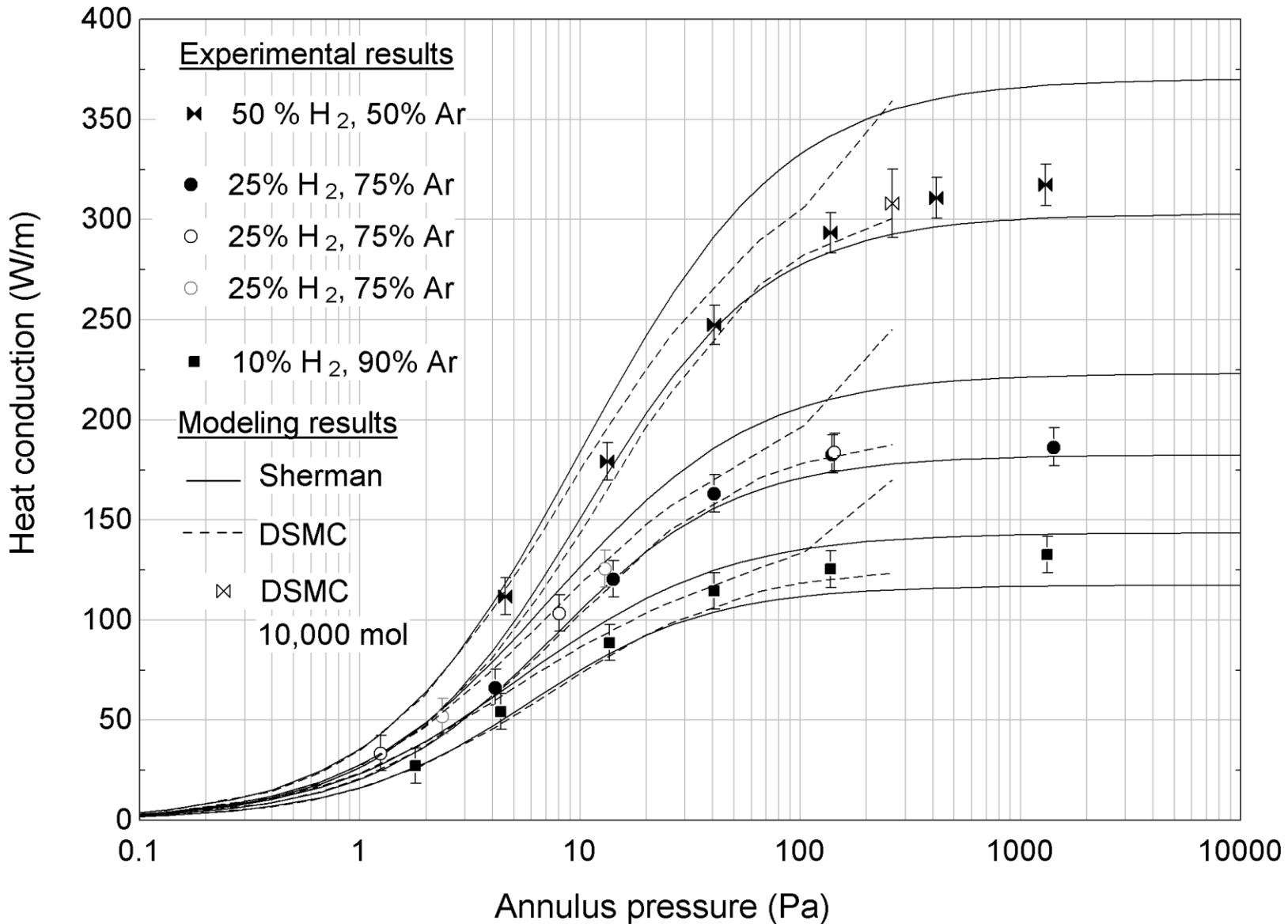
Results – Pure gases



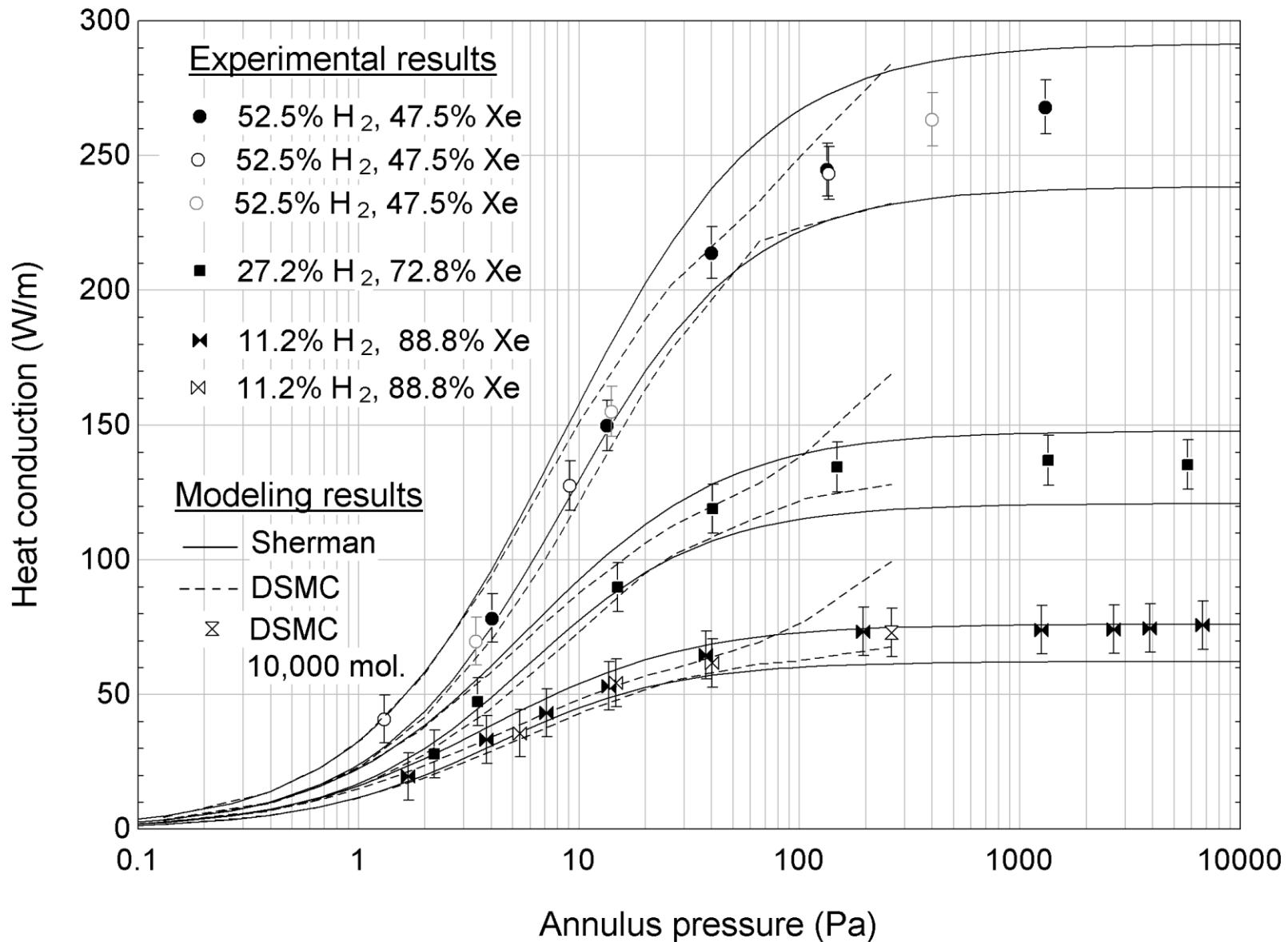
Results – Pure gases (zoomed)



Results – Hydrogen/Argon mixtures



Results – Hydrogen/Xenon mixtures



Conclusions

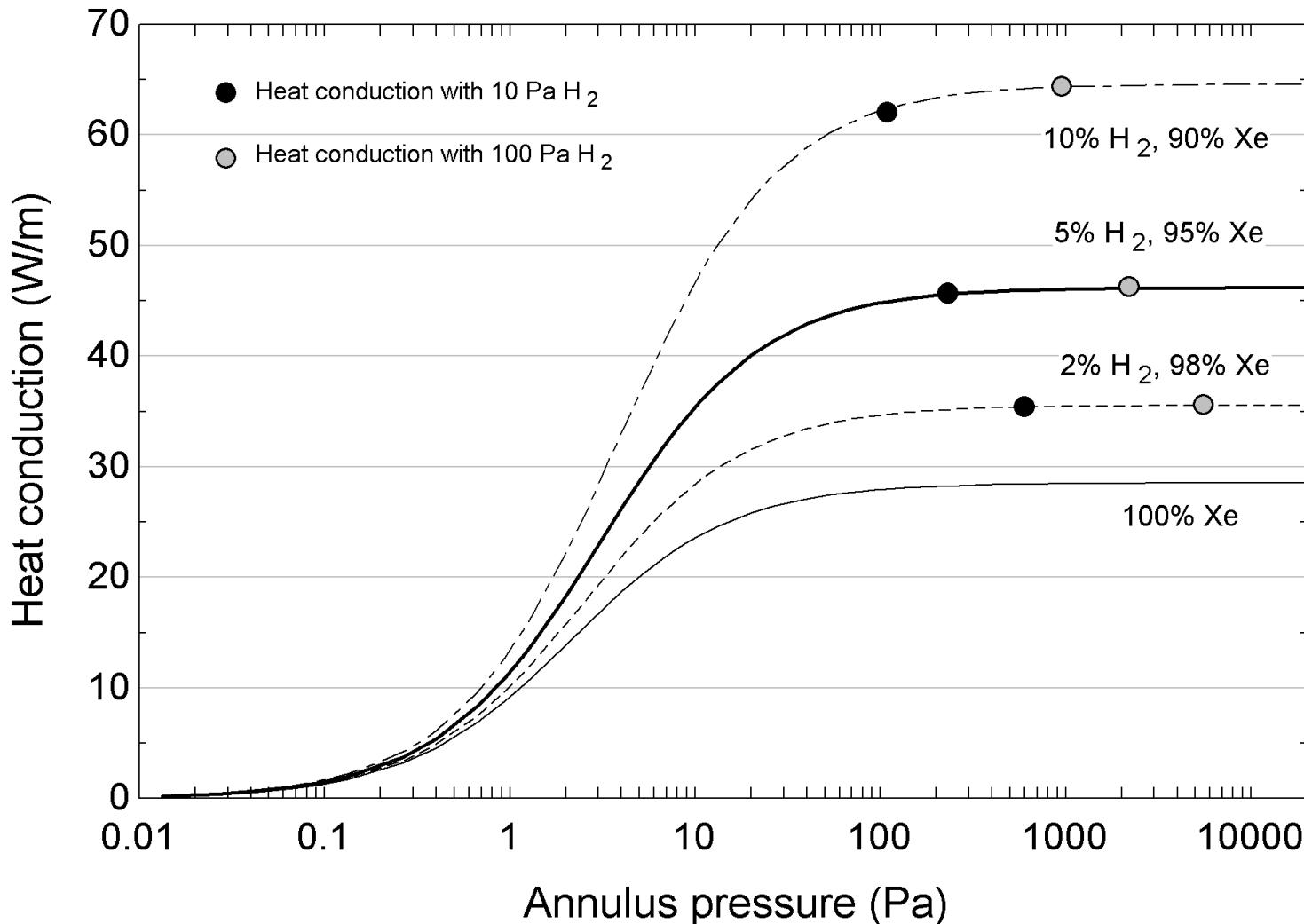


The Sherman interpolation model and DSMC models correctly predict high temperature difference, free molecular and transition regime heat conduction of Ar, Xe, H₂, and H₂/Ar and H₂/Xe mixtures in a parabolic trough receiver.

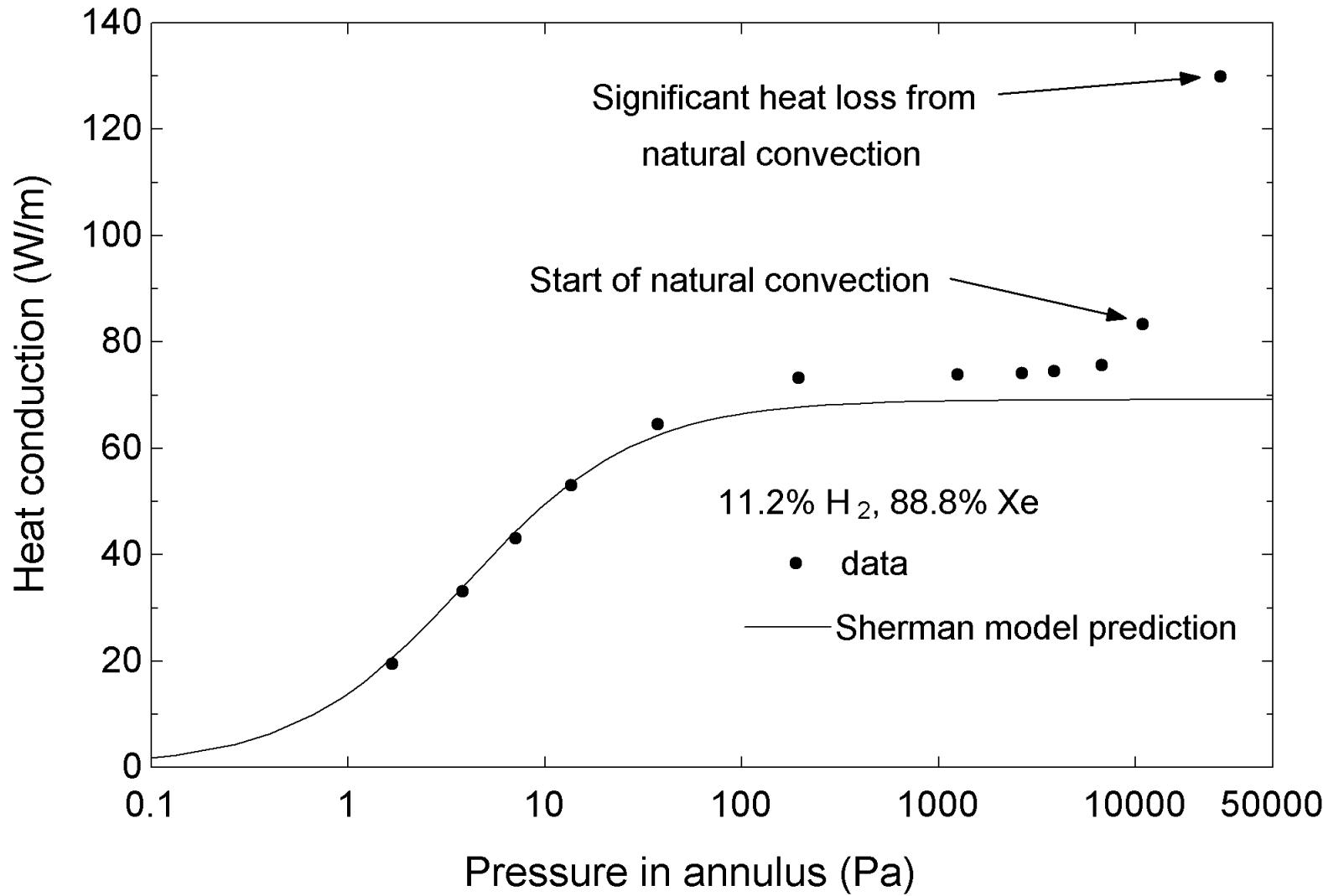
DSMC's ability to accurately correct heat conduction depends on how space, time, and the gas is discretized. Deviations from the continuum in this research were due to too few molecules used in the simulation.

Hydrogen's heat conduction can be significantly mitigated by the introduction of a large molar fraction of inert gas.

Practical considerations



Practical considerations



Acknowledgements



Mom and Dad

Schott

CSP team at NREL

DOE

Faculty at CU Boulder

Friends

Extra slides



Annular pressure of H₂ not necessarily in continuum regime

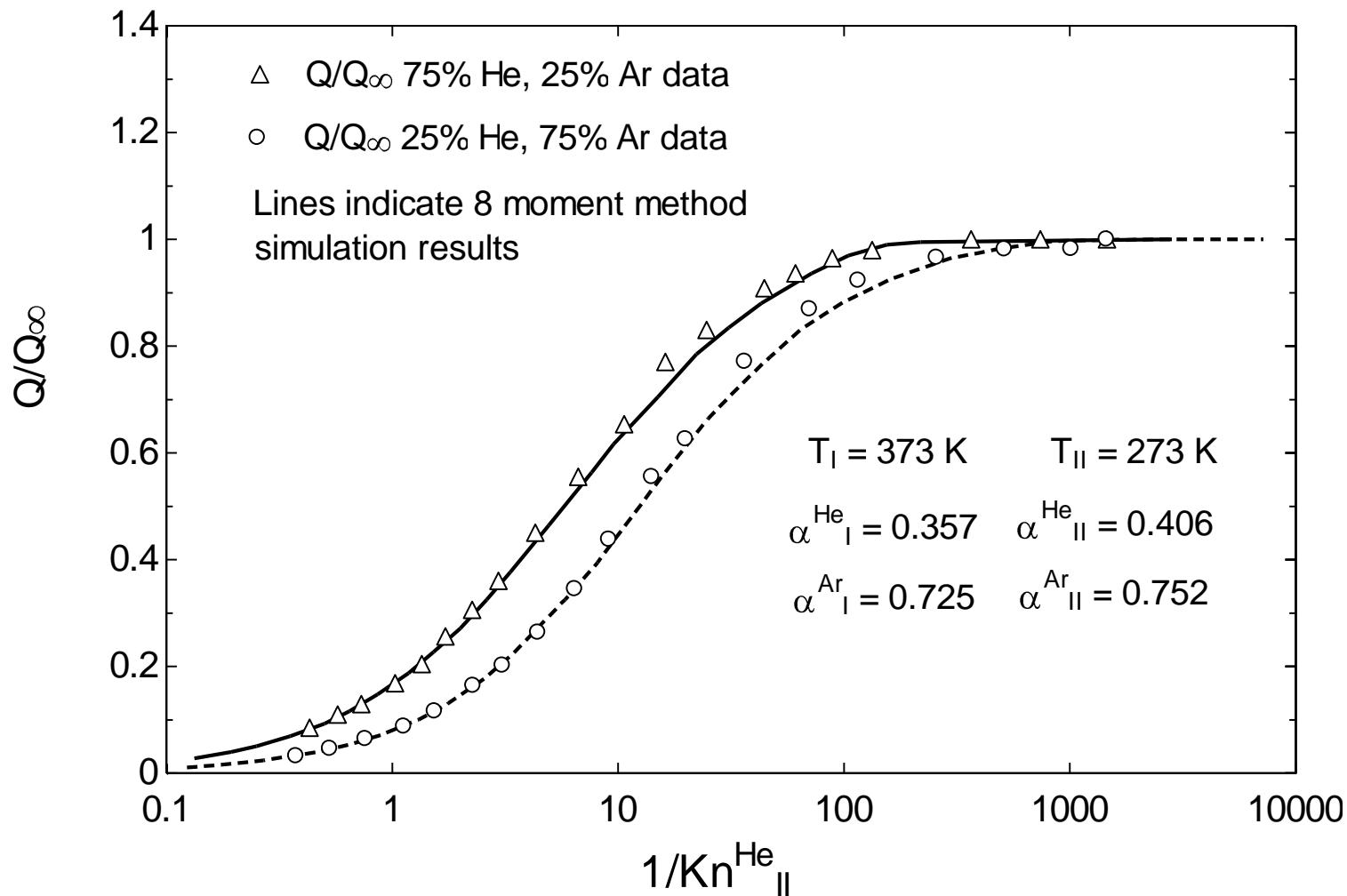


$$KnudsenNumber = \frac{MeanFreePath}{CharacteristicDimension}$$

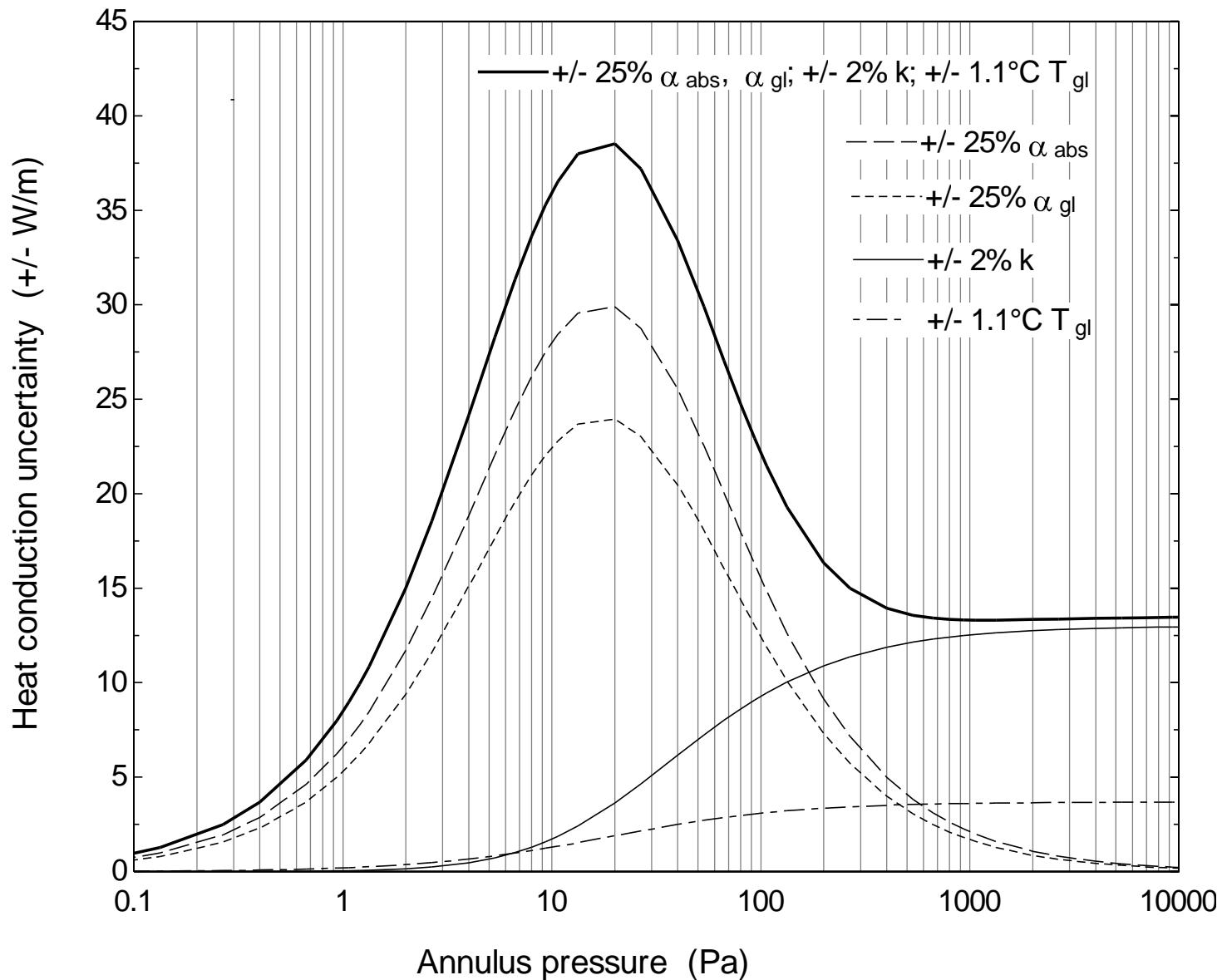
$$MeanFreePath = \frac{1}{\sqrt{2\pi} (MolecDiam)^2 (ParticleDensity)}$$

H ₂ Pressure (torr)	MFP (cm)	Knudsen number	Estimated heat conduction at T _{abs} = 450°C (W/m)	Pressure Regime
10	0.0015	0.001	1200	Continuum
1	0.015	0.01	1100	Temperature jump
0.1	0.15	0.1	600	Transition
0.01	1.5	1	100	Transition

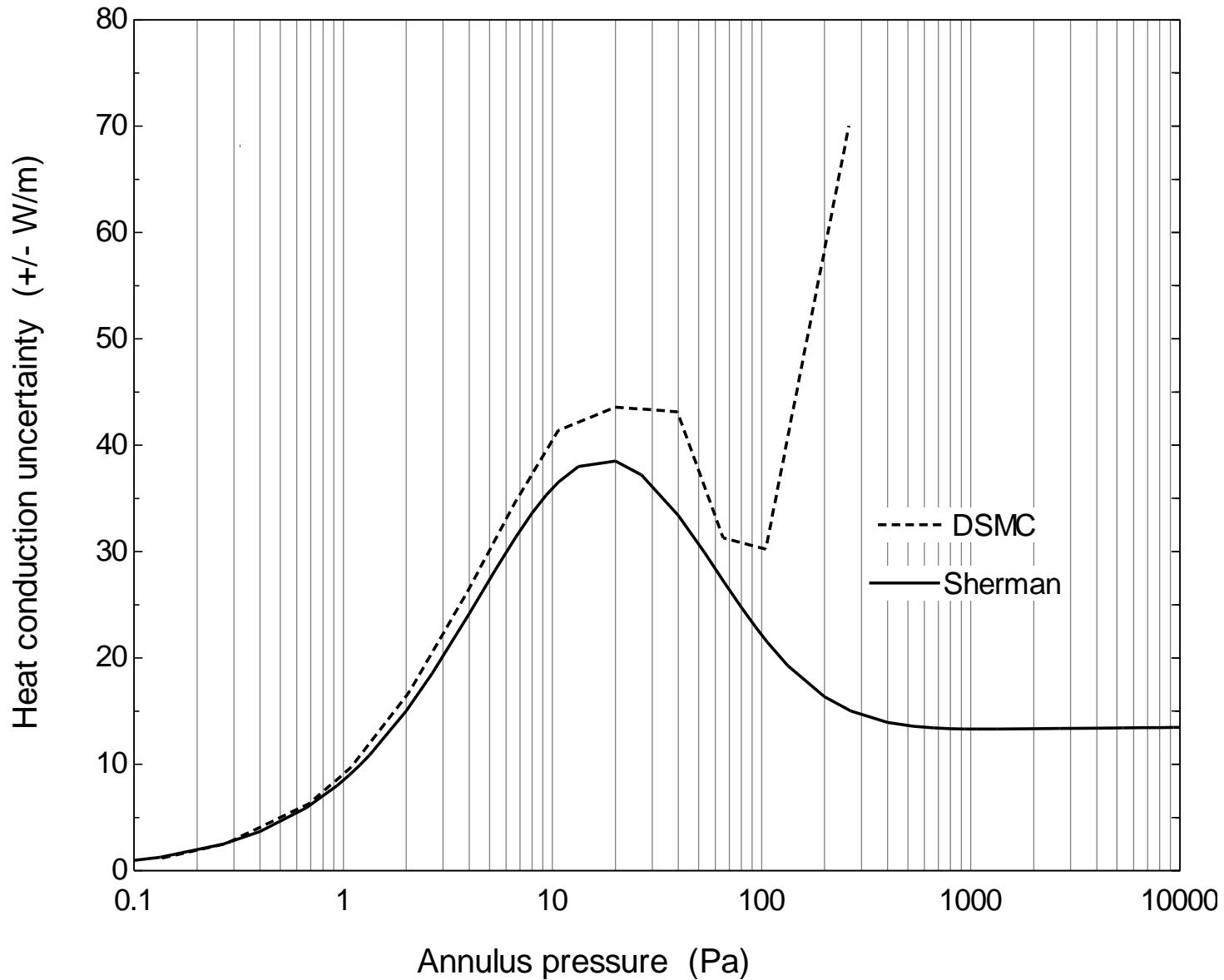
D. Braun, 1976. *Heat Transfer in Simple Monatomic Gases and in Binary Mixtures of Monatomic Gases*



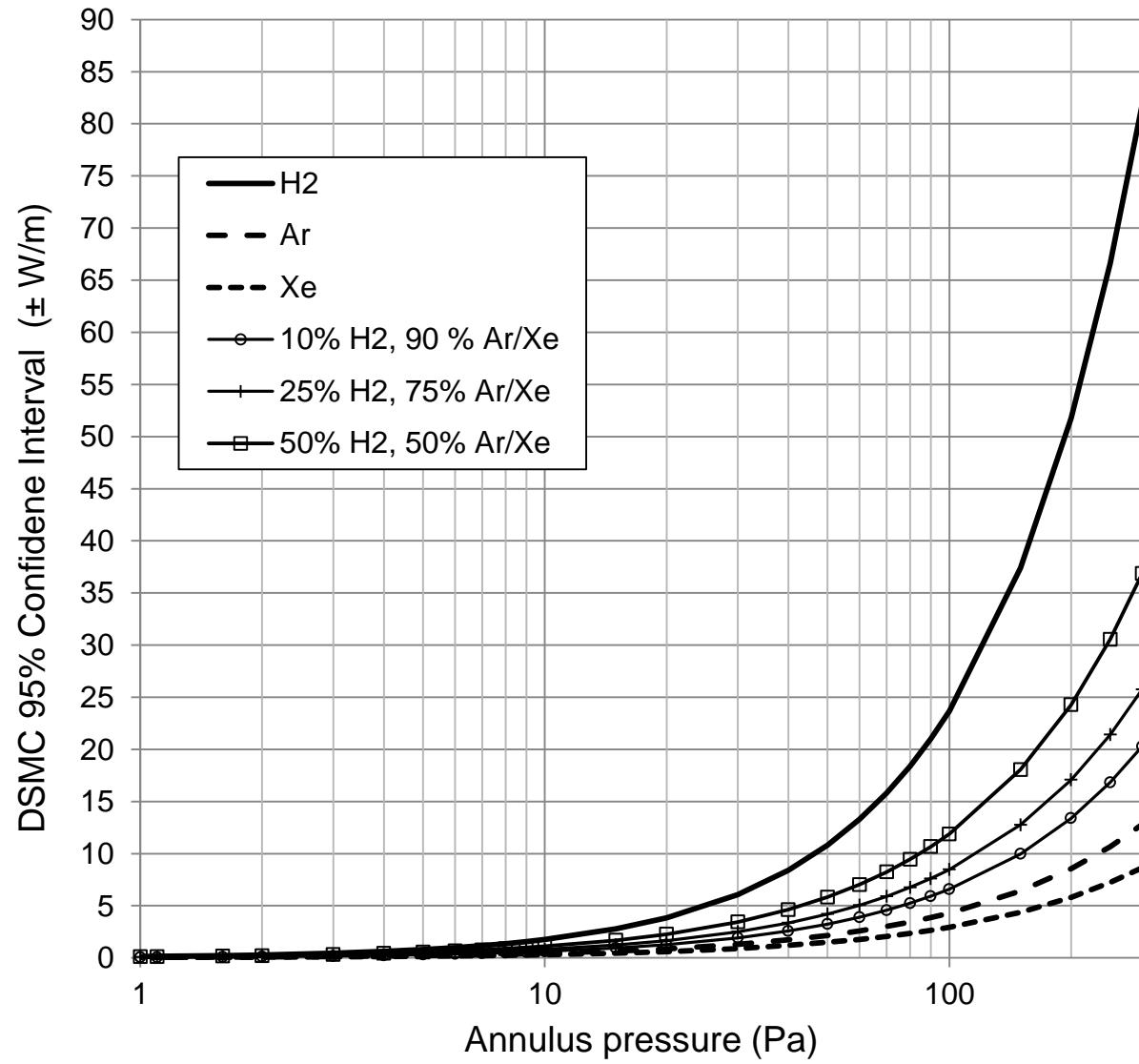
Confidence interval Sherman Interpolation formula



Confidence interval DSMC



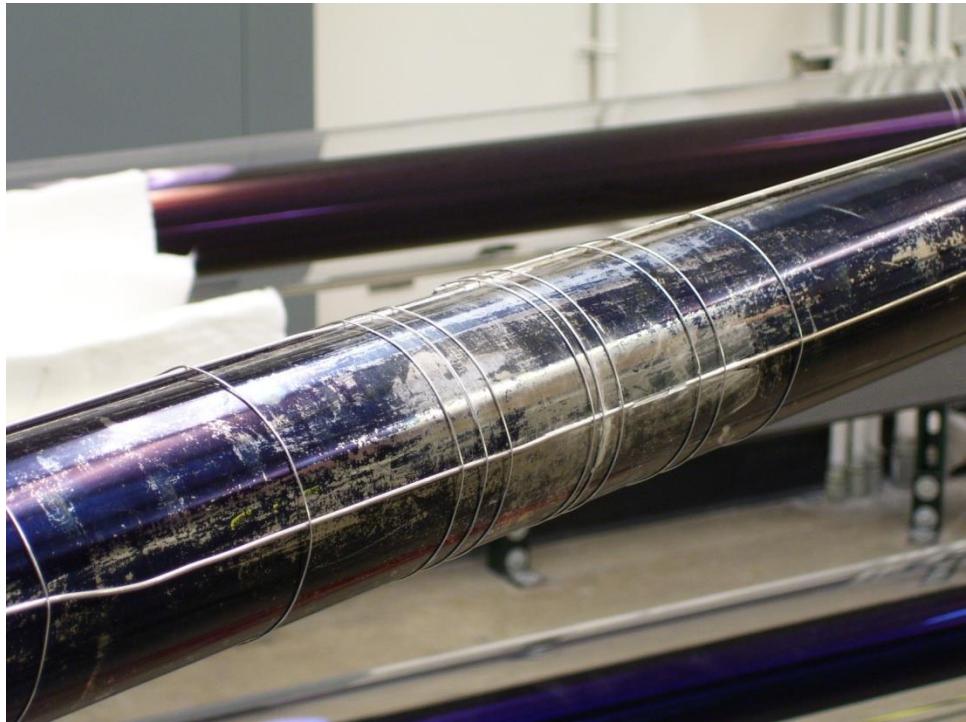
Spread of DSMC results



Heater core



Absorber over-temp set-up



Example of data taken during a run

