The Test and Prediction of Argon-Hydrogen and Xenon-Hydrogen Heat Conduction in Parabolic Trough Receivers

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Abstract

This study measures heat conduction across the annulus of a parabolic trough receiver in the free-molecular, transition, temperature jump, and continuum regimes for argon-hydrogen and xenon-hydrogen mixtures at an absorber temperature of 350°C. Experimental values are predicted successfully by Sherman's interpolation formula and the Direct Simulation Monte Carlo Method. Depending on pressure, heat conduction of hydrogen in the annulus of a receiver can be greater than 500 W/m receiver length and decrease the annual net electricity production of a parabolic trough power plant by more than 50% relative to a plant with evacuated receivers. However, heat conduction can be reduced to 50-100 W/m when hydrogen is mixed with an inert gas such that the molar fraction of the inert gas is 95% or greater. This results in annual net electricity production penalty of 3-7% instead of more than 50%. Assuming 100 Pa of hydrogen in the annulus of a current receiver, the addition of 1900 Pa of xenon or 4900 Pa of argon will effect this reduction while avoiding natural convection in the annulus.

1. Introduction

A solar parabolic trough power plant receiver is evacuated to prevent heat conduction from the approximately 300-400°C stainless steel absorber tube to the 50-70°C borosilicate glass envelope surrounding it. This vacuum is compromised as hydrogen builds up in the receiver annulus between the cylindrical absorber and glass envelope. Degradation of the heat transfer fluid (HTF) within the absorber generates hydrogen vapor pressures large enough to cause hydrogen permeation from the HTF, through the stainless steel absorber tube, into the otherwise evacuated annulus [1]. Present receiver designs attempt to limit permeation through careful selection of the absorber material and anti-permeation coatings, but also use chemical getters in the annulus to adsorb permeating hydrogen. The amount of time a receiver will operate before hydrogen causes increased heat loss depends on the amount of getter in the annulus and the hydrogen permeation rate. Current permeation rates may be small enough, and getter capacities large enough, to ensure that receivers will last 20 years before their efficiency is compromised. Unfortunately, the hydrogen vapor pressure in the HTF that drives the permeation rate is unknown. It's possible that hydrogen vapor pressures in the HTF will result in larger permeation rates than expected, thereby saturating the getters and causing undesired thermal loss within the lifetime of the receiver.

The mixing of a low thermal conductivity gas with hydrogen in the receiver annulus can substantially reduce the heat conduction relative to the conduction that occurs when hydrogen is present in the annulus alone. This gas could be introduced into the annuli of receivers in the field that have already failed, or it could be put into the annulus preemptively during the manufacturing process.

This research measures heat conduction in a receiver at an absorber temperature of 350°C for argon-hydrogen and xenon-hydrogen mixtures in the free-molecular, transition, temperature jump, and continuum pressure regimes. The goal of the research was to determine experimentally how much heat conduction was reduced when xenon or argon was mixed with hydrogen in the annulus of a parabolic trough receiver, and to find models that accurately predicted the experimental data.

2. Background

This study tests and calculates gas heat conduction in the free molecular, transition, temperature jump, and continuum regimes between the absorber tube and glass envelope of a parabolic trough receiver. This section describes these regimes and presents methods for their analysis.

In his review of rarefied gas heat transfer, Springer [2] classifies gas heat conduction regimes using the concept of the Knudsen number.

$$Kn = \frac{\lambda}{L} \tag{1}$$

Kn = the Knudsen number
λ = the mean free path of gas molecules between intermolecular collisions
L = characteristic length of the space containing the gas

Springer presents the following approximate guidelines for determining the heat conduction regime based on Knudsen number.

Kn < 0.01	continuum
0.01 < Kn < 0.1	temperature-jump
0.1 < Kn < 10	transition
10 < Kn	free molecular

In the free molecular regime heat conduction is linearly dependent on gas pressure. Ballistic transport carries energy from one surface to the other, i.e. intermolecular collisions occur infrequently so the molecules' trajectories are affected solely by impact with surfaces enclosing the gas. Knudsen [3] derived Eqn. 2 to calculate steady-state heat conduction between concentric cylinders.

$$q_{FM} = \frac{1}{\frac{1}{\alpha_1} + \left(\frac{R_1}{R_2}\right)\left(\frac{1}{\alpha_2} - 1\right)} \cdot \frac{P\left(C_v + R/2\right)}{\left(2\pi M R T_{avg}\right)^{1/2}} \cdot \left(T_1 - T_2\right) \cdot 2\pi R_1 \tag{2}$$

q_{FM} is the heat conduction from the inner cylinder (W/m length)
P is the pressure of a Maxwellian gas (velocities follow a Maxwellian distribution) at the same density as the gas between the plates at temperature T_{avg}
R_1, R_2 are the inner and outer radii, respectively
M is the molecular mass of the gas
R is the gas constant
C_v is the heat capacity of the gas at constant volume
T_1 , T_2 are the inner and outer cylinder temperatures
T_{avg} is the average temperature of the gas, approximated as $(T_1+T_2)/2$
α_1, α_2 are the accommodation coefficients of the gas on the inner and outer cylinders

Thermal accommodation coefficients are required to calculate free-molecular, transition, and temperature-jump regime heat conduction. The thermal accommodation coefficient is an empirical attempt to quantify the complicated interaction between an impinging gas molecule and molecules comprising a solid boundary. Knudsen's definition of the accommodation coefficient [4], interpreted by Kennard [3] is:

"the fractional extent to which those molecules that fall on the surface and are reflected or re-emitted from it, have their mean energy adjusted or 'accommodated' toward what it would be if the returning molecules were issuing as a stream out of a mass of gas at the temperature of the wall."

Accommodation coefficients range between 0 and 1. An accommodation coefficient of 1 signifies that a molecule's velocity after collision with a surface is determined entirely by the surface temperature, and it also signifies that energy was fully exchanged between the molecule and the surface. An accommodation

coefficient of 0 means that the molecule's post-collision velocity is identical to its pre-collision velocity and that no net energy was exchanged in the collision.

In contrast to the free-molecular regime, heat conduction in the continuum is a function of neither pressure nor accommodation coefficients. Eqn. 3 is the equation to calculate steady-state heat conduction between concentric cylinders in the continuum regime.

$$q_{continuum} = \frac{2\pi k_{gas}(T_1 - T_2)}{\ln\left(R_2 / R_1\right)} \tag{3}$$

$q_{continuum}$ is the heat conduction from the inner cylinder (W/m length)
k_{gas} is the thermal conductivity of the gas
R_1, R_2, T_1, T_2 were defined previously

The temperature-jump solution arose out of the desire to use a continuum solution in a slightly rarified gas regime, and so it modifies Eqn. 3 to account for rarefaction effects. Ratzel et al. [5] and Beikircher et al. [6] used the temperature jump method to predict heat conduction in all pressure regimes in parabolic trough receivers. Their methods' inability to account for accommodation coefficients of each gas of a binary mixture on both surfaces precluded their use in this research.

In the transition regime, the molecular mean free path is of the same order as the characteristic dimension in the flow so both intermolecular and molecule-boundary interactions affect the transport coefficients. The primary recourse for predicting transition regime quantities has been to the Boltzmann transport equation. Two notable approaches are the BGK model [7] and Lee's moment method [8]. However, existing closed form solutions of the Boltzmann equation for the concentric cylinder geometry are generally limited to small temperature differences, single species monatomic gases, and complete accommodation on one or both surfaces.

3. Modeling

O'Shea et al. [9] used Sherman's interpolation formula and the Direct Simulation Monte Carlo (DSMC) to predict heat conduction of single species polyatomic gases between the concentric cylinders of a low temperature solar collector in all pressure regimes. Both solution methods provide the flexibility to calculate large temperature difference heat conduction in a non wire-in-tube geometry for a binary gas mixture comprised of polyatomic molecules with incomplete accommodation of both gases on both surfaces.

After reviewing data on subsonic heat transfer and skin drag for multiple internal and external flow geometries, Sherman [10] proposed Eqn. 4 to predict transition regime heat conduction values from free-molecular and continuum values.

$$\frac{1}{q_{Transition}} = \frac{1}{q_{FreeMolecular}} + \frac{1}{q_{Continuum}} \tag{4}$$

$q_{\text{Transition}}$ is the heat conduction in the transition regime
$q_{\text{FreeMolecular}}$ is the heat conduction in the free molecular regime, calculated from Eqn. 2
$q_{\text{Continuum}}$ is the heat conduction in the continuum regime, calculated from Eqn. 4

The application of Sherman's formula to this research required the calculation of the thermal conductivity of the xenon/hydrogen or argon/hydrogen gas mixture using Wilke's methodology [11] and the calculation of the accommodation coefficients of gases on the aluminum oxide coating of the absorber and the silica coating of the glass envelope using Song et al.'s correlation [12]. However, the accommodation coefficient of hydrogen on the absorber surface was tested and the tested value was used in the simulations.

G.A. Bird developed the Direct Simulation Monte Carlo (DSMC) method for the study of rarefied gas flows. He wrote a book on the method [13] that provides example FORTRAN programs for various geometries. The 1-dimensional program DSMC1 was modified for this research. DSMC simulates a real gas that has between 10^{18} and 10^{22} molecules per m^3 by tracing the trajectories and collisions of several thousand molecules. The momentum, translational energy, and rotational energy of 10^{13} to 10^{18} molecules are assigned to one molecule. The trajectory of that molecule is traced in a discretized space over discrete time steps. In each time step the molecule is allowed to move, collide with a system boundary if possible, and then given the opportunity to collide with adjacent molecules.

Table 1 summarizes the DSMC inputs for this study and their respective uncertainties. The Sherman model used identical accommodation coefficients to those presented in Table 1, and the Sherman model's other major source of uncertainty was the ± 2% and ± 10% uncertainty in the pure gas and gas mixture thermal conductivities, respectively. All uncertainties presented in this paper correspond to the 95% confidence interval.

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[a]	0.66[b]	0.76[b]	±25%
Accommodation on glass	0.25[b]	0.82[b]	0.90[b]	±25%

a = calculated from experimental results in this research

b = from Song et al's correlation [12]

Table 1. Gas-related inputs for the DSMC simulations

DSMC convergence was investigated through 33 Pa. This pressure was picked to include the entire transition regime. The purpose of this investigation was to determine the number of simulated molecules, the time step, and the numbers of cells and sub-cells needed to achieve reliable results for this research. The investigation concluded with the determination of 3000 molecules, a time step equal to ½ the mean collision time at each pressure, and 20 cells with 400 sub-cells (20 sub-cells per cell). The use of more molecules, a smaller time step, or more cells or sub-cells added computation expense but did not give different results through 33 Pa.

4. Testing

Fig. 1 is a photograph of the National Renewable Energy Laboratory (NREL) Heat-Loss Test Stand. This indoor test stand uses electric resistance heaters inside the receiver to bring the absorber surface up to desired test temperatures. Once a desired temperature is reached and the system comes to steady state, power transducers measure the electrical power required to maintain the absorber temperature, measured by thermocouples. The power required is the total heat loss of the receiver. Gas mixtures at prescribed molar fractions and pressures were supplied to the receiver annulus through a glass nipple on the receiver glass. Three capacitance manometer pressure gages with complementary ranges measured the pressure during testing. A roughing pump and a turbo-pump evacuated the approximately 25 L annular volume to less than 0.001 Pa during bake-out and before testing. The system was baked-out at more than 450°C for about a month prior to testing, and it was verified that the off-gassing rate was less than 0.01 Pa/hour at the start of every test session. The annular space was evacuated between heat loss measurements. A commercial

research gas supplier provided the pure gases and gas mixtures. Certificates of analysis were provided indicating molar fraction uncertainties of ± 0.1%. The test stand, the testing procedure, hardware, gases, and safety considerations are further described in [14].

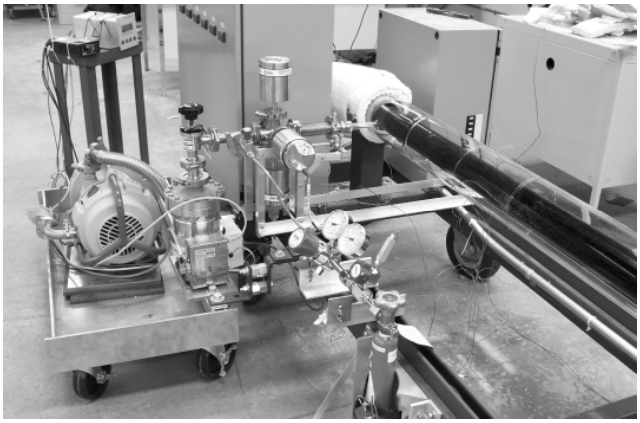

Fig. 1. NREL's heat loss test stand with vacuum and gas delivery system, pressure gauges, and specially constructed receiver. Photo by F. Burkholder, NREL.

The receiver, provided by Schott, had an open evacuation nipple that attached to the vacuum system. It was manufactured without getters. Receiver specifications vary, but the receiver for this testing had the following dimensions at 350°C.

Total length (m):	4.08	Abs. inner radius (m):	0.033	Gl. inner radius (m):	0.0595
Annulus length (m):	4.02	Abs. outer radius (m):	0.035	Gl. outer radius (m):	0.0625

Table 2. Receiver dimensions. Absorber is abbreviated Abs., and glass is abbreviated Gl.

5. Results

Early simulations indicated that modeled results were strongly dependent on the accommodation coefficient of hydrogen on the 350°C absorber surface. Therefore this accommodation coefficient was determined experimentally by both the free-molecular [15] and temperature jump methods [16]. The free-molecular method yielded 0.34 ± 25%, and the temperature jump method yielded 0.39 ± 33%. 0.34 was used in the analysis.

The pure gas heat conduction experimental results are compared to Sherman and DSMC simulation results in Fig. 2. To make the graphs easier to read, the model results are indicated by the envelope comprised by their 95% confidence intervals. Experimental data are represented by points with uncertainty bars that indicate their 95% confidence interval. The uncertainty of the modeled results in the transition regime is dominated by the ± 25% uncertainty of the accommodation coefficients, while the uncertainty in the data is dominated by the uncertainty of the power transducer (± 5 W/m) and the uncertainty induced by the ± 2 - 5°C uncertainty in the absorber temperature (± 6 – 13 W/m). The Sherman model agrees with the data for all gases in all pressure regimes, while DSMC agrees with the data through 33 Pa and to 100 Pa in some cases. The use of more simulation molecules increases the accuracy of DSMC results at higher pressures, but also lengthens simulation time due to more frequent intermolecular collisions during a time step.

Xenon and hydrogen gas mixture results are presented in Fig. 3. Many data points were repeated, as indicated by the multiple legend entries, and the data show good repeatability. Both DSMC and Sherman models predict experimental data within experimental and modeling uncertainty. Argon/hydrogen results can be found in [14] and show similar agreement between experimental and modeled results.

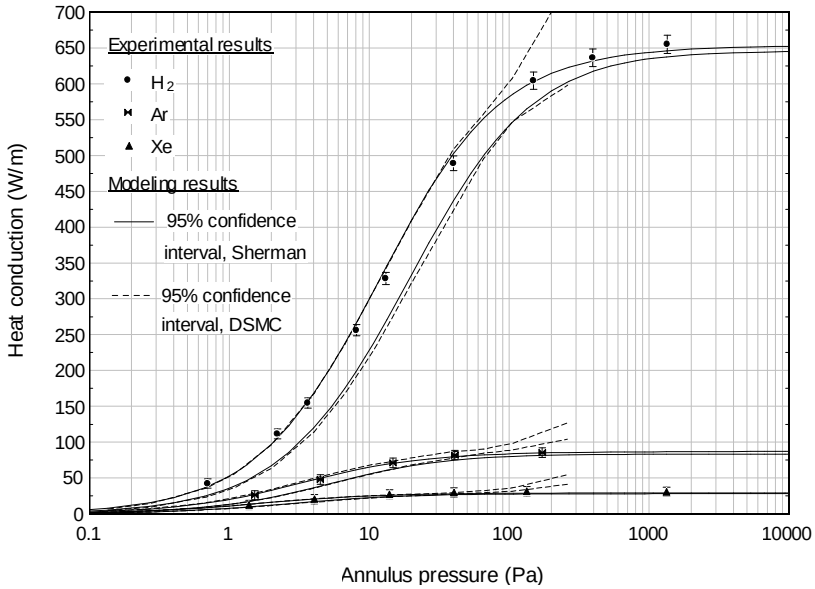

Fig. 2. Pure gas experimental and simulation results in all pressure regimes.

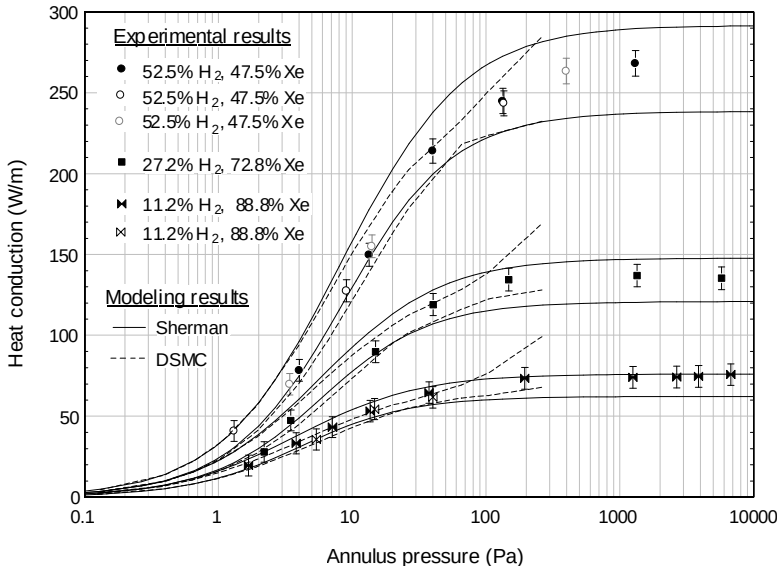

Fig. 3. Xenon/hydrogen mixture experimental and simulation results.

6. Discussion

The previous section showed that the Sherman model accurately predicts heat conduction from the free molecular through continuum pressure regimes for the pure gases and gas mixtures of this research. This fact and its ease of use recommend it for design studies investigating the amount of inert gas that should be present to mitigate heat conduction induced by hydrogen in the annulus.

Suppose it's determined that 10 Pa is the equilibrium pressure of hydrogen in the heat transfer fluid. Eventually 10 Pa will permeate into the annulus and cause an extra 274 W/m of heat loss to the environment. Fig. 4 shows that 274 W/m can be reduced to 62 W/m with the addition of 90 Pa of xenon to the annulus (10% molar fraction hydrogen) or down to 35 W/m (2% molar fraction hydrogen) with the addition of 490 Pa of xenon. Fig. 4 also shows that similar reductions are possible if 10 times more hydrogen, 100 Pa, is in the annulus.

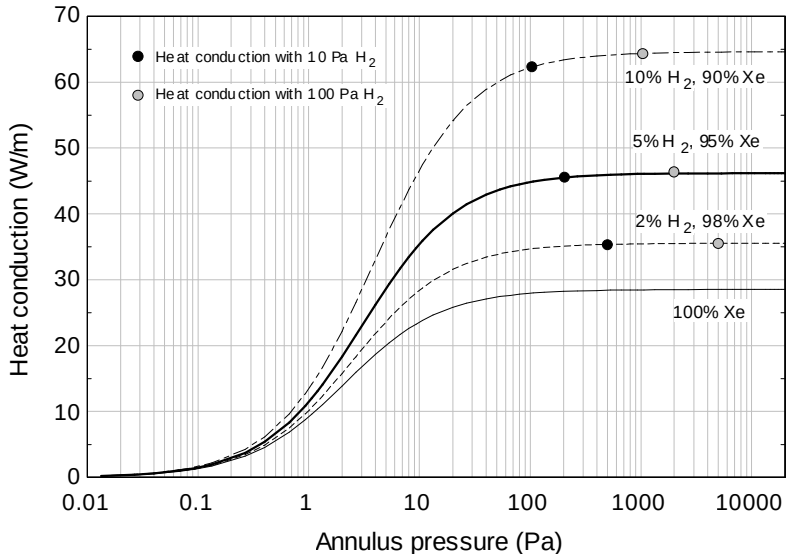

Fig. 4. Heat conduction predicted by Sherman's model for xenon/hydrogen mixtures.

The effect that these heat losses have on parabolic trough power plant performance were determined using the Solar Advisor Model [17] 100 MW_e reference plant with wet-cooling described by Turchi [18]. Default values were used, with the exception of the receiver heat loss. Table 3 summarizes the six different receiver annulus conditions that were simulated as well as the predicted net annual energy production and levelized cost of energy for each case.

Annulus Condition	Total receiver heat loss at 350°C (W/m)	Net annual electricity production (MWh)	Ratio of net annual electricity production to evacuated case	Plant levelized cost of energy, LCOE (¢/kWh)	Difference in LCOE from evacuated case (¢/kWh)
Evacuated	153	374780	1	20.6	0
1900 Pa Xe	182	367997	0.98	21.0	+0.4
100 Pa H_2 & 1900 Pa Xe	199	363413	0.97	21.2	+0.6
4900 Pa Ar	238	350693	0.94	22.0	+1.4
100 Pa H_2 & 4900 Pa Ar	247	347695	0.93	22.2	+1.6
100 Pa H_2	720	166978	0.45	45.7	+25.1

Table 3. Solar Advisor Model results for a 100 MWe reference plant with all receivers having the indicated gases in their annuli.

Ideally a solar plant will have evacuated receivers, and if a way is determined to prevent hydrogen build-up or permeation then evacuated receivers are the best performing option for parabolic trough power plants. However, if hydrogen permeates through into an otherwise evacuated receiver to reside in the annulus at 100 Pa, SAM predicts that plant performance is severely compromised: half the net electricity is produced and the levelized cost of energy more than doubles. An inert gas receiver would prevent this drastic penalty.

7. Conclusions

The Sherman interpolation model accurately predicted xenon, argon, hydrogen, xenon/hydrogen, and argon/hydrogen heat conduction in all pressure regimes in the test parabolic trough receiver of this research. DSMC predicted experimental data through 33 Pa. A receiver can be supplied with a small amount of inert gas in its annulus. A solar plant using receivers with 1900 Pa of xenon in their annuli will make 98% of the net annual electricity as a plant with evacuated receivers, with an LCOE less than half a cent per kWh higher. This assumes that there is no additional cost to the receiver to add this amount of xenon, and that receiver cost has not decreased (though it should) due to a reduced need for getters in the annulus. 4900 Pa of argon

could be added instead, though the plant would not perform as well. The Rayleigh number is less than 1000 in both cases, so natural convection is not induced. Natural convection onsets near 5000 Pa and 16000 Pa for mixtures containing large molar fractions of xenon and argon, respectively. This has been confirmed experimentally.

8. Acknowledgements

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