Study on Thermal Loss Characteristics of the Vacuum Annulus in Parabolic Trough Solar Evacuated Absorber Tubes (Postprint)

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Abstract

This study establishes a heat transfer model for rarefied gas in the vacuum annulus based on four different heat transfer mechanisms within the annular gap of parabolic trough vacuum absorber tubes under different vacuum pressures, and verifies the accuracy of the model and computational method. The heat loss values of the vacuum absorber tube and the outer wall temperature of the glass tube are calculated under three conditions: hydrogen permeation, air leakage, and glass tube rupture. The influence patterns of different gas leakages into the vacuum annulus of the absorber tube on the heat loss values of the absorber tube and the outer wall temperature of the glass tube are analyzed. The results show that hydrogen permeation has the greatest impact on the performance of the absorber tube, followed by air infiltration. Vacuum failure will significantly reduce the photothermal conversion efficiency of the collector system.

Full Text

Research on Heat Loss Characteristics of Vacuum Annulus in Parabolic Trough Solar Receiver Tubes

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Abstract

This paper establishes heat transfer models for rarefied gas within the vacuum annulus of parabolic trough receiver tubes based on four distinct heat transfer mechanisms under varying vacuum pressures, and validates the accuracy of these models and computational methods. The heat loss values and glass envelope outer wall temperatures are calculated for three scenarios: hydrogen permeation, air leakage, and glass tube rupture. The influence of different gases leaking into the vacuum annulus on heat loss characteristics and glass envelope temperature is analyzed. Results demonstrate that hydrogen permeation exerts the greatest impact on receiver tube performance, followed by air infiltration. Vacuum failure significantly reduces the photothermal conversion efficiency of the collector system.

Keywords: receiver tubes; heat transfer in rarefied gas; vacuum annulus; heat loss characteristics

Nomenclature

Symbols: - a: thermal accommodation coefficient - Cv: molar heat capacity at constant volume, J/(mol · K) - d: characteristic length, m - D: diameter, m - g: gravitational acceleration, m/s^{2}; jump distance, m - Mg: gas molecular weight - P: pressure, Pa - Pr: Prandtl number - Q: heat loss per unit tube length, W/m - R: molar gas constant - Ra: Rayleigh number - T: temperature, K - *T***: effective gas temperature - β: volumetric expansion coefficient, 1/K - λ: thermal conductivity, W/(m · K); molecular mean free path, cm - : kinematic viscosity, m^{2}/s - α: thermal diffusivity, m^{2}/s

Subscripts: - a: annulus - CO: continuum state - FM: free molecular state - i: inner - o: outer - TJ: slip flow state - TR: transition state

Parabolic trough solar thermal power generation employs numerous parabolic trough concentrators arranged in series-parallel configurations to achieve high collection temperatures, heating the working fluid to generate superheated steam that drives turbine-generator sets. Traditional trough systems use thermal oil or molten salt as heat transfer fluids. At high temperatures, long-term decomposition produces hydrogen that can permeate through the metal tube into the vacuum annulus, while atmospheric helium and other inert gases can permeate through the glass tube into the annulus. Seal damage may also cause air leakage [1][2].

This study focuses on vacuum receiver tubes for parabolic trough systems. The vacuum receiver tube is a core component of parabolic trough solar thermal power generation, and its performance critically influences overall system efficiency. Heat loss from receiver tubes represents a key factor affecting collector efficiency. During actual power plant operation, vacuum degradation in the annular space inevitably occurs, necessitating investigation into rarefied gas heat transfer effects. This paper examines heat transfer mechanisms in the vacuum annulus, establishes gas heat transfer models, analyzes heat transfer characteristics within the annular gas layer under different vacuum pressures, and obtains quantitative relationships between vacuum pressure and heat loss.

1 Vacuum Annulus Gas Heat Transfer Model

Depending on vacuum pressure, four distinct heat transfer mechanisms may dominate within the annular space. Identifying transition points between these mechanisms and selecting appropriate calculation formulas are essential.

1.1 Rarefied Gas State Determination

According to rarefied gas kinetic theory, the degree of gas rarefaction can be characterized by a dimensionless parameter called the Knudsen number (Kn):

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

A larger Kn indicates more rarefied gas conditions. Rarefied gas heat transfer states can be divided into four regimes based on Kn [3]:

1. $Kn > 10$: Free molecular flow regime
2. $10^{-1} < Kn < 10$: Transition regime
3. $10^{-3} < Kn < 10^{-1}$: Velocity slip and temperature jump regime (slip flow regime), where Fourier’ s law, Fick’ s law, and Navier-Stokes equations remain applicable
4. $Kn < 10^{-3}$: Continuum regime, where conventional heat transfer theory can be applied

1.2 Rarefied Gas Heat Transfer in Free Molecular Flow Regime

Calculations show that when annulus pressure falls below 0.013 Pa, $Kn > 10$ and the rarefied gas enters the free molecular flow regime. For concentric cylindrical heat transfer surfaces in the annulus, heat transfer (heat loss per unit tube length) can be derived from rarefied gas kinetic theory as [4][5]:

$$Q_{FM} = \frac{2\pi k_B T^*}{\sqrt{2\pi R T^*/M_g}} \cdot \frac{a_1 a_2}{a_2 D_i + a_1 D_o} \cdot (T_i - T_o) \quad (1.2)$$

where for coaxial cylindrical annuli, $b = 1$.

1.3 Rarefied Gas Heat Transfer in Transition Regime

When annulus pressure reaches 0.013-1.33 Pa ($10^{-1} < Kn < 10$), the gas state transitions to the transition regime. For concentric cylindrical interfaces, heat transfer can be calculated as:

$$Q_{TR} = \frac{2\pi \lambda_{gas}(T_i - T_o)}{\ln(D_o/D_i) + 2g/D_i + 2g/D_o} \quad (1.3)$$

$$g = \frac{2-a}{a} \cdot \frac{2\lambda_{gas}}{Pr(\gamma+1)} \cdot \frac{2-B}{B} \quad (1.4)$$

where for monatomic gases, $B = 1$; for diatomic gases, $B = 45/38$.

1.4 Rarefied Gas Heat Transfer in Slip Flow Regime

At annulus pressures of 1.33-133 Pa ($10^{-3} < Kn < 10^{-1}$), the gas enters the slip flow regime. Under these moderate-to-low pressures, temperature discontinuities occur [6]. Due to temperature jumps at solid surfaces, the effective gas gap for heat transfer increases.

Considering both monatomic and diatomic gases [7], the formulation becomes:

$$Q_{TJ} = \frac{2\pi\lambda_{gas}(T_i - T_o)}{\ln(D_o/D_i) + b \cdot \frac{2-a}{a} \cdot \frac{2\lambda_{gas}}{Pr(\gamma+1)} \cdot \left(\frac{1}{D_i} + \frac{1}{D_o}\right)} \quad (1.5)$$

where for coaxial cylindrical annuli, $b = 1$.

1.5 Rarefied Gas Heat Transfer in Continuum Regime

As annulus pressure increases above 133 Pa ($Kn < 10^{-3}$), the gas enters the continuum regime where natural convection gradually dominates annular heat transfer, causing a sharp increase in heat transfer coefficient. The calculation formula is [8]:

$$Nu = 0.42 \cdot Ra^{1/4} \cdot Pr^{0.012} \cdot \left(\frac{D_o}{D_i}\right)^{-0.25} \quad (1.6)$$

$$Q_{CO} = \frac{2\pi\lambda_{gas}(T_i - T_o)}{\ln(D_o/D_i)} \quad (1.7)$$

2 Model Validation and Simulation Results

2.1 Model Validation

For model validation, parameters from reference [9] were adopted. First, with the absorber tube temperature set at 250°C and helium as the annulus gas, heat loss variations across pressures from 0.013 Pa (10^{-4} torr) to 0.013 MPa (100 torr) were simulated. These results were compared with 15 discrete experimental pressure values from reference [9] to verify model accuracy.

Second, with nitrogen as the annulus gas at 6700 Pa (equilibrium partial pressure), heat loss variations were simulated for metal tube temperatures from 0°C to 450°C and compared with eight discrete experimental data points from reference [9] for nitrogen.

[Figure 1: see original paper]

Figure 1.1 Comparison of simulated and experimental heat loss values at various helium pressures

Figure 1.2 Comparison of simulated and experimental heat loss values at various absorber tube temperatures

Figure 1.1 compares simulated results with experimental data from reference [9] for heat loss at various helium pressures. The simulation shows excellent agreement with experimental values, confirming the accuracy of the vacuum receiver tube annulus gas heat transfer model. The simulation curves are smooth across each transition region and match literature data well.

Figure 1.2 illustrates heat loss trends with increasing metal tube temperature when nitrogen permeates the annulus at equilibrium partial pressure (6700 Pa). Again, strong agreement between simulation and experimental values demonstrates the model' s accuracy across typical temperature ranges.

2.2 Simulation Results

Simulations employed parameters similar to Solel-UVAC receiver tubes with VP-1 thermal oil as the working fluid. Three scenarios were modeled: (1) hydrogen permeation at 133 Pa (local equilibrium with hydrogen partial pressure in the oil), (2) complete air leakage at 0.1 MPa annulus pressure, and (3) glass tube rupture with direct heat exchange between the metal tube and ambient environment.

2.2.1 Hydrogen Permeation Scenario Figure 1.3 shows receiver tube heat loss and glass envelope outer wall temperature versus solar irradiation at 340°C oil temperature, 20°C ambient temperature, and 2 m/s wind speed with hydrogen permeation. Both heat loss and glass temperature increase substantially compared to good vacuum conditions. While both parameters increase linearly with solar irradiation, the effect is modest: glass temperature rises only 1.8°C and heat loss increases merely 18.2 W/m as irradiation increases from 300 to 1200 W/m^2.

Figure 1.4 presents heat loss and glass temperature versus working fluid temperature at 1000 W/m^2 solar irradiation, 20°C ambient temperature, and 2 m/s wind speed. Hydrogen permeation again causes significant increases in both parameters, with trends similar to good vacuum conditions but at elevated levels.

[Figure 2: see original paper]

Figure 1.3 Heat loss and glass envelope temperature at various solar irradiation levels (hydrogen permeation)

Figure 1.4 Heat loss and glass envelope temperature at various HTF temperatures (hydrogen permeation)

2.2.2 Air Leakage Scenario Figures 1.5 and 1.6 show glass envelope temperature and heat loss versus solar irradiation and working fluid temperature after air leakage into the annulus. The trends are consistent with good vacuum and hydrogen permeation cases, but both parameters increase substantially compared to good vacuum conditions, though less severely than with hydrogen. Under identical operating conditions, air leakage increases glass temperature by approximately 85°C and heat loss by about 620 W/m relative to good vacuum, indicating significant performance degradation.

[Figure 3: see original paper]

Figure 1.5 Heat loss and glass envelope temperature at various solar irradiation levels (air leak)

Figure 1.6 Heat loss and glass envelope temperature at various HTF temperatures (air leak)

2.2.3 Glass Tube Rupture Scenario With glass tube rupture, heat loss from the metal tube surface dissipates directly to the surroundings. Figures 1.7 and 1.8 show heat loss versus solar irradiation and working fluid temperature. While trends remain consistent with previous cases, heat loss increases dramatically—approximately 15 times higher than under good vacuum conditions at the same operating point.

[Figure 4: see original paper]

Figure 1.7 Heat loss at various solar irradiation levels (glass break)

Figure 1.8 Heat loss at various HTF temperatures (glass break)

Based on the established gas heat transfer model for parabolic trough receiver tube vacuum annuli, this study validates the model' s accuracy and simulates heat loss and glass envelope temperature under hydrogen permeation, air leakage, and glass rupture scenarios. Results indicate hydrogen permeation impacts receiver tube performance more severely than air leakage, and that vacuum failure makes receiver tubes more sensitive to ambient conditions while significantly reducing collector system photothermal conversion efficiency. These conclusions provide theoretical guidance for future design and operation of parabolic trough solar receiver tubes.

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