DESIGN OF AN EXPERIMENT TO MEASURE THE THERMAL ACCOMMODATION COEFFICIENT BETWEEN HELIUM AND STAINLESS-STEEL IN CONCENTRIC CYLINDERS

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ABSTRACT

Heat transfer through a 1 mm gap between two concentric cylinders representing the gap between a fuel support basket and a canister is experimentally and numerically investigated. The objective of this work is to study rarefied gas heat transfer in a simple geometry, and to measure the thermal accommodation coefficient at the interface between stainless steel and rarefied helium. The thermal accommodation coefficient is used to characterize the interaction between gas molecules and wall at the molecular level. It is important to determine its value with precision for better determination of heat transfer at low pressure. The experimental procedure consists of measuring the temperature difference between the inner and outer cylinders as the pressure is decreased in the gap. By knowing the heat flux across the gap the thermal accommodation coefficient can be extracted from the theoretical expression relating the temperature difference to the radial heat flux. Three-dimensional simulations using the ANSYS/Fluent commercial code are conducted to assess on the design of the experimental apparatus. These simulations confirmed that the apparatus design is effective to study the heat transfer across rarefied gas and to determine the thermal accommodation coefficient for helium on stainless steel surface.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>a</td>
<td>Slope of the temperature difference variation with the inverse of the pressure</td>
</tr>
<tr>
<td>Kn</td>
<td>Knudsen Number</td>
</tr>
<tr>
<td>k</td>
<td>Boltzmann constant, $1.38 \times 10^{-23}$ [m²kg/s²K]</td>
</tr>
<tr>
<td>L</td>
<td>Length [m]</td>
</tr>
<tr>
<td>m</td>
<td>Molecular mass of gas [kg]</td>
</tr>
<tr>
<td>P</td>
<td>Pressure [Pa]</td>
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<tr>
<td>Pr</td>
<td>Prandtl number</td>
</tr>
<tr>
<td>$Q_r$</td>
<td>Radial heat flux [W]</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature [K]</td>
</tr>
<tr>
<td>R</td>
<td>Radius of the cylinders [m]</td>
</tr>
</tbody>
</table>

Greek symbols

- $\alpha$: Thermal accommodation coefficient
- $\gamma$: Specific heat ratio
- $\kappa$: Thermal conductivity of the gas [W/mK]
- $\lambda$: Mean free path [m]
- $\mu$: Stress viscosity of the gas [kg/ms]
- $\zeta_T$: Temperature Jump Coefficient

Subscript

- $0$: Reference
- $A$: Inner cylinder
- $B$: Outer cylinder
- $g$: Gas
- $w$: Wall

Acronyms

- CFD: Computational Fluid Dynamics
- DSMC: Direct Simulation Monte Carlo
- DVM: Discrete Velocity Method
- TAC: Thermal Accommodation Coefficient

INTRODUCTION

Nuclear fuel assemblies consist of fuel rods containing high radioactive fuel pellets and fission product gases, held in square arrays by a header, a footer and periodic spacer plates [1]. Following their discharge from the reactor, used fuel assemblies are stored underwater while their heat generation rate and radioactivity decrease. After five or more years, [2] a canister is lowered into the pool and the fuel assemblies are placed inside it. The canister is closed, lifted out of the pool and drained. Before the canister is sent for storage it is subjected to a vacuum drying operation to remove the remaining water and moisture. It is important that all the water and moisture be removed to prevent corrosion of the fuel cladding and internal structures, and the creation of a flammable mixture of oxygen and hydrogen within the canister [3]. After drying, the canister
is filled with helium to pressures between 3 and 7 atm (306 to 711 kPa), sealed, and the final cover lid is bolted or welded in place.

With the absence of a defined used-fuel disposal and/or reprocessing path, it is crucial to assure the safety of long-term dry cask storage systems [4]. Federal regulations (10CFR72) require that “spent fuel cladding must be protected during storage against degradation that leads to gross ruptures or the fuel must be otherwise confined such that degradation of the fuel during storage will not pose operational safety problems with respect to its removal from storage.” The cladding is the primary confinement barrier for the used fuel pellets and fission gas. Its integrity must be protected to assure that, after decades in storage, the assemblies can be safely transferred to other packages, and/or transported to other locations. Radial hydride formation within the cladding has the potential to radically reduce cladding ductility and its suitability for transport or long term storage [4].

During all post-reactor drying, transfer, storage, and transport operations the fuel cladding must be kept below the temperature limit of 400°C (673K), specified by the Nuclear Regulatory Commission (NRC) Interim Staff Guidance-11, Revision 3 (ISG-11) [5], to avoid (a) dissolution of circumferential hydrides that exist in the cladding and (b) high gas pressures within the tubes, which leads to high cladding hoop stress [5]. If these hydrides dissolve and the hoop stresses become large, then as the heat generation of the used fuel decreases during long-term storage radial hydrides may form and cause the cladding to become brittle [6-9]. Vacuum drying operation [10] may be the most likely event to cause the fuel temperature to exceed the temperature limit. This is because it is the first operation when the fuel is removed from water and placed in a gas-filled environment, while the fuel heat generation is still relatively high.

During the vacuum drying operation the pressure in the canister is decreased to as low as 67 Pa to promote evaporation and removal of remaining water [3]. Several cycles of evacuation and refill are required before the operator can demonstrate that the canister satisfies the technical specifications of maintaining pressure of 400 Pa (3 Torr) for 30 minutes [10, 11]. Because of the low pressures and densities associated with vacuum drying, buoyancy-induced gas motion and natural convection heat transfer within the helium gas can be neglected. The thermal conductivity of the gas is almost the same as it is at atmospheric conditions. Moreover, the rarefaction condition (low pressure) induces a notable temperature difference (temperature jump) at the interface between wall surfaces and gas [3, 12-15]. As the pressure decreases this temperature jump increases and causes the cladding temperature to increase.

The temperature jump is characterized by the thermal accommodation coefficient [16, 17]. At low pressure the collisions between gas molecules and the surfaces dominate the molecules-molecules collisions. In these conditions the continuity of the macroscopic parameters (velocity and temperature) near the walls are not achieved. The concept of the accommodation coefficient was introduced by Maxwell during the mid-nineteenth century [18]. The thermal accommodation coefficient ($\alpha$) is related to the temperature of incident $T_i$ and reflected $T_r$ molecules as

$$\alpha = \frac{T_r - T_i}{T_r - T_w}$$

where $T_w$ is the wall temperature. The value of $\alpha$ varies from 0 to 1. In the case $\alpha=0$, the molecules are reflected specularly, without transferring any of their momentum or energy to the surface (the molecule’s temperature and velocity component parallel to the wall remain unchanged, but its velocity normal to the wall is reversed). For $\alpha=1$, the molecules are reflected diffusely: a molecule leaving the surface “forgets” all information upon collision and it leaves accommodating the surface properties (i.e., their average bulk velocity is equal to the surface velocity and the temperature is equal to the temperature of the surface). A lower value of $\alpha$ leads to a higher temperature jump between the wall and gas molecules interacting with it.

The values of $\alpha$ were determined experimentally for a wide range of surfaces and gas molecules, using different methods [19-21]. Its value depends on a number of parameters, such as the type of gas, surface material, its cleanliness and its roughness. Authors [19, 20] reported values of $\alpha$ close to 1 for heaviest molecules and smaller values for lighter molecules. The value of $\alpha$ reported for the pair helium-stainless steel [20] is in the range [0.2, 0.4] for $T=700$ K to 300 K. The values $\alpha=1$, 0.4 and 0.2 will be used in the current work for all the calculations.

**Current Work** The long term objective of the current research is to develop and experimentally benchmark computational models that predict the temperature difference between the cladding and basket walls during vacuum drying operation. An experimental apparatus that consists of 8×8 array of heated rods enclosed in square-cross-section-pressure-vessel subjected to vacuum condition will be constructed. The measurements will be compared to the computational model that will include the temperature jump boundary condition at the gas/surface interfaces. To achieve this objective experimental measurements of the thermal accommodation coefficient between stainless-steel surface and helium gas is conducted. The experimental design consists of coaxial cylinders’ geometry filled with helium gas. The temperature and heat flux from the inner cylinder (hotter) to the outer cylinder (colder) will be measured and the thermal accommodation coefficient will be obtained from the comparison between the measurements and an analytical model. The aim of the current paper is to discuss the results obtained from the simulated model of the experimental apparatus that will be used to measure the value of the thermal accommodation coefficient. Three dimensional simulations are performed using ANSYS/Fluent package that accurately represent the experimental apparatus. Conduction and radiation heat transfer simulations are performed with rarefied helium gas filling the gap region between the stainless-steel cylinders. The temperature of the outer cylinder is maintained at a constant value of 300K and the pressure is varied from $10^5$ to 100 Pa.
Experiments will be performed with matching heat generation rates and pressure ranges to that of the ANSYS/Fluent models, while maintaining the constant outer temperature using a water jacket.

RAREFIED GAS CONDITIONS AND HEAT TRANSFER

At low pressure conditions the number of collisions between gas molecules and solid surfaces is low compared to the normal atmospheric conditions. The continuity of the macroscopic parameters of temperature and velocity near the wall is not achieved. At these pressures some special characteristics related to the gas rarefaction can be observed. The principal parameter characterizing rarefied gas is the Knudsen number (Kn), which is calculated as

\[ Kn = \frac{\lambda}{L_c}, \]

where \( \lambda \) is the mean free path defined as the distance travelled by molecules between two successive collisions [22] and \( L_c \) is a representative physical length scale. Typically the characteristic length \( L_c \) is the smallest dimension in the system. The mean free path \( \lambda \) is defined as

\[ \lambda = \frac{\mu}{P} \left( \frac{2kT}{m} \right)^{1/2}, \]

where \( P \) and \( T \) are the pressure and the temperature, respectively. \( k \) is the Boltzmann’s constant, \( m \) is the mass of the gas molecule, \( \mu \) is the dynamic viscosity, whose temperature dependence is determined using the intermolecular interaction Hard Sphere (HS) model [23] as

\[ \mu = \mu_0 \left( \frac{T}{T_0} \right)^{1/2}, \]

where \( T_0 \) is the reference temperature equal to 273.15 K and \( \mu_0 \) is the reference viscosity, which depends on the gas. It is equal to 1.865×10⁻⁵ Pa·s for helium.

The Knudsen number is used as a parameter to describe the gas rarefaction level. Using this parameter four regimes of rarefaction can distinguish: (i) The continuum regime (\( Kn \leq 10^{-5} \)), where the flow and heat transfer can be accurately modeled using the classical Navier-Stokes and Convective Energy equations. The number of collisions is large enough to reach the continuity of parameters at the wall. (ii) The slip regime (\( 10^{-3} \leq Kn \leq 10^{-2} \)), where the number of molecule-surface collisions are not enough to reach equilibrium near the wall, but far from the wall equilibrium is reached. In this regime the Navier-Stokes and Convective Energy equations are appropriate but they must be subjected to the conditions of velocity-slip and temperature-jump at the wall. (iii) Transitional regime (\( 10^{-4} < Kn < 10 \)), it is the most difficult regime for modeling. In this regime the mean free path is comparable to the characteristic length scale, therefore, the collisions between molecules and surfaces dominate the collisions between molecules. To model the flow in this regime the Boltzmann equation should be solved using the Discrete Velocity Method (DVM) [24, 25] or Direct Simulation Monte Carlo (DSMC) method [23]. (iv) The free molecular regime (\( 10 \leq Kn \)), where the gas is highly rarefied and the flow is driven by the collisions between molecules and surface. In this regime the flow is modeled using the collisional kinetic Boltzmann equation.

It should be pointed out that all the regimes cited above can be accurately modelled using the kinetic theory, by solving the Boltzmann equation. Nevertheless, it is inefficient to implement this equation or other kinetic equations for gas flow simulation in the hydrodynamic and slip regimes because of the large computational efforts needed for their solution.

EXTRACTION OF THE THERMAL ACCOMMODATION COEFFICIENT

The measurement of the accommodation coefficient can be either performed in the slip or free molecular regimes. In these two regimes the analytical expression relating the thermal accommodation coefficient to the temperatures of inner and outer walls can be obtained. For the pressures experienced during vacuum drying operation of fuel canister the gas is in the slip regime. For this reason only the slip regime is considered in this paper.

In the slip regime the interaction between molecules and the wall does not allow equilibrium near the wall to be reached, meaning that there is a discontinuity of temperature and velocity near the wall (\( T_g \neq T_w \) and \( V_g \neq V_w \)), which is called as temperature jump or velocity slip boundary conditions. In order to obtain the analytical expression of temperature difference between the inner and outer cylinders as function of pressure, heat flux and accommodation coefficient the Navier-Stokes and Convective Energy equations are used and subjected to the temperature jump boundary condition.

Sharipov [26] suggested that when gas is in the slip regime with the assumption of the temperature difference between two concentric cylinders \( \Delta T \) is smaller than the average temperature \( T_w (\Delta T<<T_w) \) and without considering the radiative heat flux, the radial heat flux across the gas may be expressed as

\[ Q_r = 2\pi L\kappa \Delta T \left[ \ln \frac{R_B}{R_A} + \xi_T \lambda \left( \frac{1}{R_A} + \frac{1}{R_B} \right) \right]^{-1} \]

where \( R_A \) and \( R_B \) are the radii of the inner and outer cylinders, respectively. \( L \) and \( \kappa \) are the length of the cylinders and thermal conductivity of the gas, which is assumed to be constant for the small temperature difference \( \Delta T=T_i-T_B \), where \( T_i \) and \( T_B \) are the temperature of the inner and outer cylinders, respectively. In equation (5) \( \xi_T \) is the temperature jump coefficient. It was demonstrated in previous work [27] that the expression of
EXPERIMENTAL DESIGN

Figure 1 shows drawing of the experimental setup, which consists of a main inner cylinder system centered inside an outer cylindrical vessel. The inner cylinder system has an outer diameter of 43.51 mm and the vessel cylinder has an inner diameter of 45.49 mm, which leaves a gap of about ~1 mm between the two cylinders. The length of the inner cylinder system is 1.032 m, however the length of the vessel cylinder is 1.132 m. In order to keep a constant gap between the cylinders the experiment is oriented vertically to avoid the problem of inner cylinder system bowing.

The main inner cylinder system is composed of an electrical heating cartridge that is centered inside a thick walled aluminum cylinder. Twelve thermocouples were strategically placed inside precision 0.15 mm deep grooved channels machined on the outer surface of the aluminum cylinder and secured with highly thermal conductive cement so that any potential gaps are minimized. The shrink fit process was used to insert the aluminum cylinder inside 1 mm thickness stainless-steel-sheath, which comprises the outer surface of the inner cylinder system. This process was used to ensure an intimate contact between the outer aluminum surface and inner stainless-steel-sheath surface. Figure 2a shows a picture of the end of the inner cylinder system with the centered heating cartridge, aluminum cylinder and stainless-steel sheath along with the thermocouples channels. The aluminum cylinder has a thick wall to allow uniform temperature profile on the outer surface of the inner cylinder system. The heating cartridge is secured in place with highly-conductive epoxy.

Low thermal conductivity (κ = 0.06 W/mK) alumina insulation material, with a thickness of 50 mm, is placed on both ends of the inner cylinder system, then the assembly (inner cylinder system + insulations) is centered inside the outer vessel cylinder with the aid of stainless-steel supports and spacer plates. This low thermal conductivity insulation is employed to minimize the heat losses from the ends of the cylinder system. The supports provide rigidity and ability to hold the inner system concentric to the vessel so that a 1 mm-wide gap is created between the two.

The temperature of the outer vessel is controlled using an external water jacket. Twelve thermocouples are placed inside small grooves machined on the outer surface of the vessel to monitor the vessel temperatures. The thermocouples where secured inside the grooves with epoxy and aluminum straps to ensure their ability to withstand the turbulence of the water flow. Figure 2b shows the water jacket that surrounds the main vessel with the thermocouple and water inlet ports.

Conflat flanges on both ends of the vessel are used to seal and maintain the pressure inside the vessel. One of the flanges contains thermocouple and power feedthroughs (not shown) to allow the connection of the thermocouples and power leads from the vacuum chamber to the outside. The other flange contains a vacuum tree (not shown) that connects the vacuum chamber to the vacuum pump through an open/close valve. To the vacuum tree is also connected a high pressure helium tank through a
variable valve that allows to set the pressure inside the vacuum chamber.

The emissivities of the vessel inner surface and stainless-steel sheath outer surface are measured, and are 0.152 and 0.149, respectively.

VALIDATION OF THE EXPERIMENTAL DESIGN

A geometrically accurate three-dimensional model of the experimental apparatus is created and meshed using ANSYS/Fluent Computational Fluid Dynamics (CFD) commercial code. Simulations that include conduction and radiation heat transfer, and temperature-jump at the interface between solid surfaces and gas are performed. The outer surface of the vessel was maintained at constant temperature of 300K and the pressure in the gap was varied from atmospheric pressure to $P = 200$ Pa. This range of pressures covers both continuum and slip regimes. Three values of the thermal accommodation coefficient, $\alpha = 1, 0.4$ and 0.2, and a constant heat generation within the cartridge heater ($Q = 150$ W) are considered for all the simulations. The expression of temperature jump coefficient proposed by Lin and Willis [28] (see Eq. (6)) is implemented in ANSYS/Fluent simulations.

These simulations are used to check the ability of the apparatus to measure $\alpha$ with high confidence. The effect of heat losses from the cylinder’s ends on the extraction of the thermal accommodation coefficient is investigated. The assumptions of constant temperature and heat flux profiles along the $z$-axis is verified.

RESULTS AND DISCUSSION

Figure 3 shows a typical cross-section-temperature-contour for all of the simulated cases considered in this paper. The maximum temperature is located at the center of the inner cylinder assembly with nearly uniform temperature through the aluminum cylinder and stainless-steel sheath surrounding the aluminum cylinder. A steep decrease in temperature is observed across the helium gas gap.

Figure 4 shows the profiles of the temperature along the $r$-axes shown in Fig. 3 for $\theta = 0^\circ$ (across the thermocouple) and $\theta = 45^\circ$, for $Q = 150$ W, and a continuum condition ($P = 1$ atm). The temperature profiles along the two axes are very similar and the only difference is obtained at the thermocouple’s location, where the thermocouples experience slightly lower temperatures difference of the order of 0.1 K. Even when varying the heat generation rate $Q$ from 150W to 300W the temperature difference across the thermocouple remains small (less than 0.15K). This systematic error in thermocouple temperature reading is included in the calculation of the thermal accommodation coefficient uncertainty (Eq. (11)).

In Fig. 5 the effect of rarefaction on the increase in temperature, compared to the continuum model, is shown. The rarefaction simulations are performed for $P = 300$ Pa and $\alpha = 1, 0.4$ and 0.2. From Figure 5 it can be seen clearly that the rarefaction effects are negligible.
model predicts higher temperature in comparison to the continuum model, which is due to the temperature-jump at the interface between solid surfaces and gas. This temperature increases as the thermal accommodation coefficient decreases (see Fig. 5).

Temperature profiles along the cylinder axis (z-axis, see Fig. 1) are shown in Figure 6 for outer surface of the stainless-steel sheath and thermocouples region. These profiles are obtained using the continuum model. A nearly uniform temperature along the stainless-sheath-surface is obtained. The maximum variation of temperature along this surface is less than 0.1 K with the maximum value obtained at the midplane.
Axial heat flux profiles along the side surfaces of the stainless-steel-sheath and vessel are shown in Figure 7. It is clear from this figure that the heat flux leaving the outer surface of the stainless-steel-sheath and delivered to the inner surface of the vessel, which are in contact with helium, are nearly identical and uniform along the axial axis direction. The maximum variation of the heat flux along the axial axis is less than 1%.

Heat losses from both ends of the inner cylinders system are minimized by choosing a cylinder with small aspect ratio $R_i/L = 0.02$, where $R_i$ and $L$ are the radius and length of the inner cylinders system, respectively, and by placing low thermal conductivity alumina insulation material ($\kappa = 0.06$ W/m.K) with 50 mm thickness on both ends of the inner cylinders system. In Eq. (7) it is assumed that all the heat generated by the cartridge heater leaves from the side surface of the inner cylinders system. Table 1 shows the percentage of the estimated heat leaving from the side and ends surface of the inner cylinders system for continuum and rarefied models with three different values of thermal accommodation coefficient. The heat leaving the end surfaces is affected by the rarefaction; as the pressure or $\alpha$ decrease the heat loss from the end surfaces is higher, however it is small and therefore Eq. (7) can be utilized to extract the value of $\alpha$ with considering this heat loss in the calculation of the uncertainty on $\alpha$.

The uniformity of the temperature and heat flux leaving the surfaces in contact with helium, shown in Figs 6 and 7 confirms the validity of the actual experimental design to be used for the calculation of the value of the thermal accommodation coefficient $\alpha$ from Equation (7).

**CONCLUSION**

The rarefied gas condition during vacuum drying of nuclear canister could potentially have a significant effect on used nuclear fuel cladding temperature. The cladding temperature increases as the pressure decreases. This increase in temperature is a result of the temperature jump that is induced between the gas and the solid surfaces. The temperature jump is dependent of the thermal accommodation coefficient. The objective of this paper is to verify the design of an experimental apparatus that will be used to determine the thermal accommodation coefficient at the interface between stainless steel and rarefied helium.

**TABLE 1** PERCENTAGE OF HEAT LOSS FROM THE SIDE AND ENDS OF THE INNER CYLINDER SYSTEM.

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>Side-Walls</th>
<th>End-Walls</th>
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</thead>
<tbody>
<tr>
<td>Continuum</td>
<td>99.66</td>
<td>0.34</td>
</tr>
<tr>
<td>$P = 300$Pa</td>
<td>99.13</td>
<td>0.87</td>
</tr>
<tr>
<td>0.4</td>
<td>98.97</td>
<td>1.03</td>
</tr>
<tr>
<td>0.2</td>
<td>98.88</td>
<td>1.12</td>
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</table>

Three-dimensional simulations using the ANSYS/Fluent code were used with thermal accommodation coefficient values of $\alpha=1$, 0.4 and 0.2, $P=1$ atm (continuum model) and 300 Pa (temperature jump model) with $Q_i = 150$W. The results for the temperature jump model were 15 K higher than the continuum model results (no temperature jump, Fig. 5) when the thermal accommodation coefficient was decreased from 1 to 0.2.

The Fluent simulations showed also that the implantation of the thermocouple in the design did not significantly change this temperature. The temperature difference between the thermocouple and the stainless-steel-sheath surface in contact with helium was less than 0.1K.

The total uncertainty on the determination of the thermal accommodation coefficient was estimated to be less than 5.2%. Currently the experimental apparatus is being constructed.
ACKNOWLEDGMENTS
This work was supported by the US Department of Energy Office of Nuclear Energy University Program.

REFERENCES