Validated Simulations of Heat Transfer From a Vertical Heated-Rod Array to a Helium-Filled Isothermal Enclosure

Measurements of heat transfer from an array of vertical heater rods to the walls of a square, helium-filled enclosure are performed for a range of enclosure temperatures, helium pressures, and rod heat generation rates. This configuration is relevant to a used nuclear fuel assembly within a dry storage canister. The measurements are used to assess the accuracy of computational fluid dynamics (CFD)/radiation simulations in the same configuration. The simulations employ the measured enclosure temperatures as boundary conditions and predict the temperature difference between the rods and enclosure. These temperature differences are as large as 72 °C for some experiments. The measured temperature of rods near the periphery of the array is sensitive to small, uncontrolled variations in their location. As a result, those temperatures are not as useful for validating the simulations as measurements from rods near the array center. The simulated rod temperatures exhibit random differences from the measurements that are as large as 5.7 °C, but the systematic (average) error is 1 °C or less. The random difference between the simulated and measured maximum array temperature is 2.1 °C, which is less than 3% of the maximum rod-to-wall temperature difference. [DOI: 10.1115/1.4037493]

Introduction

Nuclear fuel assemblies consist primarily of $7 \times 7$ to $17 \times 17$ arrays of fuel rods held in place by periodic spacer plates [1,2]. Each rod is a sealed zircaloy cladding tube containing uranium dioxide fuel pellets and pressurized gas. The pellets become highly radioactive and generate heat while they are within a reactor. After removal from a reactor, used fuel is stored under water while its radioactivity and heat generation decrease. After sufficient time, a canister with an internal basket, which has multiple square-cross section openings to support individual assemblies, is placed in a transfer cask. The cask and canister are lowered into the water, loaded with assemblies, covered, lifted from the pool, and drained. Vacuum drying [3,4] is commonly used to remove remaining moisture. This reduces possible corrosion and/or formation of combustible mixtures. The canister is then filled with atmospheric or higher pressure helium, sealed, and placed in other packaging for onsite dry storage or offsite transport.

In some storage facilities, the canister is placed vertically inside a concrete structure. Within the canister, heat generated by the assemblies causes helium to flow upward in the basket openings, and downward in vertical passages near the canister periphery. This thermal siphoning cools the fuel assemblies beyond the levels that would exist due to conduction and thermal radiation alone. Thermal siphoning is governed by the ratio of buoyancy to viscous forces, which is characterized by the Grashof number [5]

$$Gr = \frac{gB(T_m - T_w)p^2L^3}{\mu^2} \tag{1}$$

In this expression, $g$ is the gravitation acceleration, $B$ is the gas coefficient of thermal expansion, $T_m$ is the maximum cladding temperature, $p$ and $\mu$ are, respectively, the average gas density and dynamic viscosity, and $L$ is the height of the heated fuel rods.

Based on simulations for a canister that contains 24 fuel assemblies [6], the Grashof number is of the order $Gr \sim 10^6$.

After an assembly is removed from a reactor, its cladding must not exceed temperatures of approximately 400 °C [7]. This helps to avoid the formation of radial hydrides, which may embrittle the cladding and make the used fuel assembly unsuited for subsequent transport and/or processing. The computational models Heating5, ANSYS/Mechanical, COBRA-SFS, and ANSYS/FLUENT have been used to construct two-dimensional (2D) and three-dimensional (3D) models of whole loaded canisters [8–11]. These models are used to predict cladding temperatures relative to different canister environments for a range of fuel heat generation rates and helium pressures. Some of these simulations accurately model the geometry of fuel rods within each basket opening [6], while others use a “smearered” fuel blocks with an effective thermal conductivity to model each assembly [12,13]. Internal temperatures at a limited number of locations within loaded canisters have been measured in a variety of packaging designs and pressures [14,15]. Comparison of simulated temperatures with these data have been used to assure that the simulations accurately predict (or conservatively over-predict) canister temperatures [16].

These validated whole-canister simulations are useful for predicting the total temperature difference between the cladding and the canister environment, and the relative magnitude of temperature differences across certain canister components. For example, the temperature difference between the environment and canister surface, as well as those across helium-fill regions within the canister, is generally larger than the differences across metal components, whose thermal conductivities are relatively high [6]. However, loaded canisters are very large and complex structures. If a whole-canister simulation correctly predicts certain measured temperatures, there is no assurance that it accurately calculates conductive, convective, and radiation heat transfer in every portion of the canister. As a result, the validated simulation may have limited utility when predicting how design changes of individual canister components affect cladding temperatures.

The temperature differences across the helium-filled regions between the basket and cladding surfaces are significantly larger than those across metal components [6]. Heat transfer across those
regions is affected by conduction, natural convection, and radiation, and its geometry is somewhat complex. A number of experiments [17–20] have measured temperatures of enclosed arrays of heated rods, which are similar to a used fuel assembly within a support basket opening. These data have been used to validate computational fluid dynamics (CFD) simulations [21–24]. However, the range of rod heat generation rates, contained gas composition and pressure, and/or enclosure temperatures are not sufficient to validate the whole range of operating conditions.

The goal of the current work is to experimentally validate results from ANSYS/FLUENT CFD simulations for a configuration that is relevant to a helium-filled region inside a basket opening of a used fuel canister. An earlier experiment measured temperatures within an apparatus consisting of a vertical 8 × 8 array of electrically heated rods held in place by stainless steel spacer plates at either end, within an aluminum helium-filled pressure vessel [23,24]. In this paper, we consider data from that work for atmospheric and higher pressures, which are relevant to postdrying conditions. An ANSYS/FLUENT model of the apparatus is developed, and simulations are performed for a range of gas pressures, vessel, and spacer plate temperatures, and rod heat generation rates. The ability of ANSYS/FLUENT to accurately reproduce the measured temperatures is assessed. In this work, we define configuration errors as temperature variations that are caused by experimental geometric and boundary conditions that cannot be precisely controlled. This work attempts to identify locations where these errors are large, because measurements at those locations are not as useful for validating simulations as those where the errors are small.

Experimental Apparatus

The experimental apparatus is designed to represent a section of a fuel assembly between consecutive spacer plates, within a helium-filled basket opening [23,24]. A disassembled view is shown in Fig. 1. It consists of (a) an 8 × 8 array of heater rods, (b) two stainless steel spacer plates, and (c) a square anodized-aluminum enclosure. Each heater rod is 1.1 cm in diameter and 67.3 cm long. The sheath of each rod is made of 0.7 mm-thick Incoloy with compressed magnesium oxide (MgO) inside. Most of the rods are mildly bowed such that the center of some rods is as much as 3 mm away from a line connecting the rod ends. Each rod contains a Nichrome heater coil. The coil ends are anchored to metal pins in both rod ends, which are connected to external power leads. The manufacturer specifies that heat generation is uniform along the length of the heater rods to within ±6%, except for 3.2 cm sections on both ends, which are unheated. For the 64 rods, the average and standard deviation of the heater resistances are, respectively, 4 Ω and 0.12 Ω. Sets of eight heater rods are connected in series. The resulting eight sets are connected in parallel to a 0–1000 W regulated DC power supply.

The stainless steel spacer plates are 0.635 cm-thick and 11.9 cm on each side. Both contain sixty-four 1.15 cm diameter holes that hold the heater rods in position. The hole center-to-center pitch is 1.44 cm. A small threaded hole is centered between each set of four rod holes. To hold the heater rods in position, a bolt with an expansion ring is tightened in the threaded holes. The expansion ring pushes the rods to make them contact the far sides of the rod holes. This eccentricity and the rod bowing lead to small but random (uncontrolled) variations of the rod locations.

To make the enclosure reasonably isothermal, it is constructed by tungsten inert gas-welding four 2.54 cm thick aluminum plates. The surfaces are black anodized. Its interior forms a 12 cm by 12 cm square, and its total length is 91.5 cm. Figure 2(a) shows a dissection view of the assembled experiment. The heater rod array is centered axially within the enclosure, so there are 12 cm voids on each end to house power and thermocouple wires. The z-axis is shown, with its origin at the axial midplane. When in operation, the heater rods are vertical, and the gravity vector g is oriented in the negative z-direction. The inner surfaces of the spacer plates are at z = ±30.5 cm, and are coplanar with the ends of the heated regions of the rods.

Forty-seven of the 64 heater rods contain Type-K (chromel/alumel) thermocouples, at one of four axial locations, z = −17.3, 0, 17.3, and 29.2 cm. These locations are known to tolerances of ±1.3 cm, and are indicated in Fig. 2(a). In each instrumented rod, a chromel wire exits at one end while an alumel wire exits at the other. Stainless steel endplates with O-rings are bolted to both ends to seal the enclosure. The top endplate has extension tubes with feedthroughs at their ends for thermocouple leads. The bottom endplate has a thermocouple/power feedthrough and another tube that is used to evacuate and backfill the enclosure. That tube is connected to a tree with an atmospheric valve, an evacuation valve connected to an oil filter attached to an oil-based vacuum pump, and high and low pressure gauges. To increase the enclosure temperature, fiberfrax insulation blankets, with thickness of either 2.5 or 5 cm, are used on the enclosure and endplates. Figure 2(b) is a picture of the assembled apparatus wrapped in insulation.

In this sealed enclosure, buoyancy is expected to cause helium to flow upward in the warm center of the rod array, and downward
near the relatively cool enclosure walls. This is somewhat different from the thermal siphoning pattern that exists in vertical storage canisters described earlier.

Figure 3 is a schematic of the experimental apparatus cross section. The x and y coordinate system is also shown. The circles represent heater rods. Each is named according to its row (A–H) and column (1–8) location. The number inside certain rods represents the z-location of the thermocouple within that rod. The 17 rods without numbers do not contain a thermocouple. Twelve thermocouples are installed in the enclosure walls to measure its temperature. Figure 3 shows wells in the middle of each wall whose ends are 0.25 cm from the inner surface. Each wall has wells at z = −29, 0, and 29 cm. In Fig. 3, the four black-filled X’s near the center, top, and upper corners of the rod array show the x,y-locations of thermocouples that are on both the top and bottom spacer plates. The open X near the bottom right corner indicates the position of a thermocouple that is only on the top spacer plate.

The section of the experiment in Fig. 3 is symmetric about the x- and y-axes, and diagonal lines connecting heater rods A1-H8 and rods H1-A8. Due to the nearly isothermal enclosure walls, symmetry of the experiment geometry and the expected natural convection flow pattern, rods that are symmetrically located on either side of the symmetry planes are expected to have nearly the same temperatures. Greek letters \( \alpha, \beta, \gamma, \delta, \epsilon, \zeta, \) and \( \eta \) in Fig. 3 identify rods in seven symmetry groups that contain thermocouples. Table 1 lists the rods in each groups, and the \( z \)-locations of the thermocouples within them. The \( z \) group is the one that is closest to the array center, and the \( \beta, \gamma, \delta, \epsilon, \zeta, \) and \( \eta \) groups are located increasing further away.

Table 1 and Fig. 3 show that symmetry groups \( \alpha, \beta, \) and \( \eta \) have thermocouples at all four elevations, \( z = −17, 0, 17, \) and 29 cm. In this work, measurements from each group are assembled to construct an axial profile for a typical rod in that group. Based on distances of each group from the center of the array, groups \( \alpha, \beta, \) and \( \eta \) are expected to contain, respectively, the hottest, second hottest, and coolest rods in the array.

All the thermocouples in symmetry groups \( \gamma, \delta, \epsilon, \) and \( \zeta \) at \( z = 0 \). Based on symmetry, the temperature of the \( N = 6 \) or 7 thermocouples within each of these groups will be nearly identical. However, within each group, the indicated temperature may differ by normally distributed random amounts due to measurement and configuration errors. Configuration errors are caused by small but uncontrolled variations in the heater resistances, rod bowing, thermocouple placement in a rod, small variations in the enclosure temperature, and other factors. While measurement errors are expected to be roughly the same for all symmetry groups, configuration errors are not the same. In this work, the variation in temperatures within each of these groups is used to determine the variation of configuration errors with group location.

### Temperature Measurements

Table 2 describes the conditions of two experiments that are presented in this paper. Experiments are performed for two insulation thicknesses \( l = 2.5 \) or 5 cm, three nominal helium pressures \( P_N = 1, 2, \) and 3 atm (which are measured when the apparatus is at room temperature), and three rod heat generation rates \( Q = 100, 300, \) and 500 W. For each experiment, Table 2 gives its Roman numeral experiment number, Ex8, the measured pressure \( P \) when the experiment reached steady-state conditions (which are higher than \( P_N \) due to the higher steady-state temperature), and Grashof number (Eq. (1)). For the Grashof calculation, \( T_W \) and \( T_H \) are the maximum-rod and average-wall temperatures, and \( L \) is the heater rod length. The experiment Grashof numbers range from \( Gr = 10^4 \) to \( 10^8 \), which are one to 2 orders of magnitude smaller than a nominal value for a vertical used fuel canister, \( Gr = 10^9 \). As described earlier, the flow pattern in the current experiment is also somewhat different from that of canisters.

All twelve experiments were performed in a laboratory where the temperature was controlled to be approximately 23°C. The enclosure, spacer plate, and rod temperatures were measured using a data acquisition system at a sampling rate of 1 samples/min. When the heaters were off and the apparatus reached steady-state, all the thermocouples indicated approximately the same temperature, within a standard deviation of 0.5°C. After the heater rods are powered, approximately 25 h were required for the temperatures to reach steady-state conditions. After steady-state was reached, all temperatures were sampled for at least 30 min, and then averaged. The uncertainty of each thermocouple measurement was ±1.1°C.

The symbols in Fig. 4 show measured enclosure, spacer plate, and heater rod temperatures versus axial \( z \) location for experiments III \( (l = 2.5 \text{ cm}, \ P = 3 \text{ atm}, \ Q = 100 \text{ W}, \ Gr = 8 \times 10^5) \) and VII \( (l = 2.5 \text{ cm}, \ P = 1 \text{ atm}, \ Q = 500 \text{ W}, \ Gr = 1 \times 10^7) \). The temperature profile shapes in the two plots are similar, but their temperature scales are different. The solid circles at the bottom of each plot show the temperatures on all four enclosure walls at the three axial locations. At each elevation, the temperatures are not the same on the four walls, but the average temperature increases with elevation due to natural convection. For each experiment, the four triangles at \( z = −29 \) cm and five triangles at \( z = 29 \) cm show the temperatures of, respectively, the bottom and top spacer plates. Both plates are warmer than the enclosure, and the top plate temperature is higher than the bottom plate, again due to the natural convection inside the apparatus. As expected, on both spacer plates, the plate centers are hotter than locations near the enclosure walls.

### Table 1 Heater rods within each symmetry group

<table>
<thead>
<tr>
<th>Group name</th>
<th>Group heater rods</th>
<th>Locations of thermocouples</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>D4, D5, E4, E5</td>
<td>All z</td>
</tr>
<tr>
<td>( \beta )</td>
<td>C4, C5, D3, D6, E3 E6, F4, F5</td>
<td>All z</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>B4, B5, D2, D7, G4, G5</td>
<td>( z = 0 )</td>
</tr>
<tr>
<td>( \delta )</td>
<td>A4, A5, D1, D8, E1, H4, H5</td>
<td>( z = 0 )</td>
</tr>
<tr>
<td>( \epsilon )</td>
<td>A3, A6, C1, F1, F8, H3</td>
<td>( z = 0 )</td>
</tr>
<tr>
<td>( \zeta )</td>
<td>A2, A7, B1, B8, G1, H2, H7</td>
<td>( z = 0 )</td>
</tr>
<tr>
<td>( \eta )</td>
<td>A1, A8, H1, H8</td>
<td>All z</td>
</tr>
</tbody>
</table>
For both experiments, the open squares, diamonds, and circles show temperatures measured at four different axial locations within, respectively, the z (hottest), β (second hottest), and η (coolest) rod symmetry groups. The z and η temperatures are measured in different rods, as described in Table 1. The β temperatures (diamonds) are measured in eight different rods, and have two measurements at all four elevations. For the β temperatures, the two temperature measurements at locations z = −17, 0, and 17 cm are approximately the same, whereas at z = 29 cm, the temperatures differ by 1–3 °C. This was observed in all twelve experiments. As described earlier, these differences are caused by configuration and measurement errors.

The Grashof number for experiment III is eight times larger than that for experiment VII. For experiment III, in rod groups z and β, the temperatures at z = −17 cm are lower than they are at z = 17 cm. However, the temperatures at these locations are closer to each other in experiment VII, in which the effect of natural convection is less significant. The solid and dotted lines in Fig. 4 are simulated temperatures for the z, β, and η group rods, which are described in the Simulation Results section. The boundary conditions for those simulations are the measured enclosure wall and spacer plate temperatures, which are described in the Boundary Temperatures section.

Boundary Temperatures

In this work, the average measured enclosure wall temperature, \( T_W \), is used to characterize each experiment. The horizontal lines in Figs. 4(a) and 4(b) show averages in experiments III and VII which are, respectively, \( T_W = 67^\circ C \) and 218°C. In Fig. 4(a), the symbols connected by solid lines show \( T_W \) versus the total rod heat generation rate \( Q \), for all 12 experiments. As expected, the average enclosure temperature increases with heat generation rate and insulation thickness. The data for \( I = 2.5 \text{ cm} \) indicate that the average enclosure temperature is essentially independent of the gas pressure.

Figure 5(a) also shows the average temperature differences between the spacer plates and the enclosure walls. The symbols connected by dotted lines show data for the top spacer plate, \( T_T - T_W \), while dashed lines are used for the bottom spacer plate, \( T_B - T_W \). For all experiments, the upper spacer plate is warmer than the bottom. For \( I = 2.5 \text{ cm} \), the temperature differences are more strongly affected by the heat generation rate than the pressures considered in this work. As the pressure increases, the top spacer plate gets slightly hotter and the bottom spacer gets slightly cooler, but the change for these pressures is less than 2°C. Increasing the pressure increases the gas density, Grashof number, and the effect of natural convection. This causes the hottest locations on the rods to move to higher \( z \)-elevations, and explains why the top spacer plate temperature increases and the lower one decreases as pressure increases. Figure 5(a) also shows that the temperature difference between the spacer plates and the wall is significantly smaller for \( I = 5 \text{ cm} \) than for \( I = 2.5 \text{ cm} \). As already noted, the thicker insulation makes the apparatus hotter, which increases radiation heat transfer. This decreases the temperature difference between the enclosure walls and spacer plates.

To quantify the temperature variations within the enclosure wall, we define the temperature range that statistically contains 95% of the measured values, assuming they are normally distributed. This deviation temperature is twice as large as the sample standard deviation, and is calculated as [25]

\[
D_W = 2 \sqrt{\frac{\sum (T_W - T_{W,i})^2}{N_W - 1}}
\]  

(2)

In this expression, \( T_{W,i} \) is each individual measured wall temperature, and \( N_W = 12 \) is the number of wall measurements. The nonsmoothness of the walls, and measurement errors, causes \( D_W \) to
be nonzero. The top and bottom spacer plate deviations, $D_T$ and $D_B$, which are calculated using Eq. (2) but employing the top (T) and bottom (B) plate temperature measurements, assess measured temperature variations within those objects.

Figure 5(b) presents the measured temperature deviation versus heat generation rate for the three objects: the enclosure wall (symbols connected with solid lines), and the bottom (dotted lines) and top (dotted lines) spacer plates. The temperature deviation increases as the heat generation (and consequently, object temperature) increases. For $I = 2.5$ cm, the enclosure wall deviations increase marginally with gas pressure. The wall temperature deviation increases with insulation thickness because the insulation increases the wall temperature. For the top and bottom spacer plates, the deviations are nearly the same at $P = 2$ atm. However, as the pressure increases, the deviations on the top spacer plate increase (as its average temperature increases), while those of the bottom spacer plate decrease (as its average temperature decreases). The temperature deviations on the spacer plates are smaller for $I = 2.5$ cm than they are for $I = 5$ cm. This is because as the insulation thickness increases, the experiment temperature and the radiation heat transfer increase, which makes the experiment temperatures more uniform. Even though the enclosure is physically larger than the spacer plates, its deviations are smaller. This is due to higher thermal conductivity of aluminum compared to that of stainless steel. Comparing Figs. 5(a) and 5(b) shows that the temperature deviation in the spacer plates is not negligible compared to the average temperature difference between those plates and the enclosure.

### Configuration Errors

As described earlier, all rods in symmetry groups $\gamma, \delta, \epsilon,$ and $\zeta$ have thermocouples at $z = 0$. The variations within each of these groups are used to quantify each group’s configuration errors, which are caused by uncontrolled experimental geometric and boundary conditions. To do this, the average and deviation (Eq. (1)) temperatures of each of these four symmetry group were calculated for each of the 12 experiments. The Modified Thompson Tau test was used to determine if any samples within these 48 populations were statistically unlikely members of its population. As a result, measurements from rod H5 were removed for all 12 experiments, and those from rod A7 were removed from experiments I to IX. After these 21 thermocouple measurements were eliminated, the average ($T_\gamma, T_\delta, T_\epsilon,$ and $T_\zeta$) and deviation ($D_\gamma, D_\delta, D_\epsilon,$ and $D_\zeta$) temperatures were determined for all four symmetry groups and all 12 experiments.

Figure 6 is a plot of the temperature deviation for each group $D_j$ (for $j = \gamma, \delta, \epsilon,$ and $\zeta$) versus the average temperature difference between the group and the wall $T_j - T_w$. Data from all 12 experiments are presented. Dotted lines that are fit to the results of each group are included to better show trends in the data. For each group, the deviation in temperature increases roughly linearly with the temperature difference.

The deviations in Fig. 6 are caused by both measurement and configuration errors. We expect the measurement errors from each group to be roughly the same, so the differences between groups are caused by the difference in configuration errors in each symmetry group. The configuration error is smallest for the $\gamma$ group, which is the one that is closest to the array center. The errors for the $\delta$ and $\epsilon$ groups, which are the second and third closest groups, are larger than those for the $\gamma$ group. The $\zeta$ group, which is the furthest from the array center, has a lower error than those of the $\delta$ and $\epsilon$ groups.

To understand this behavior, we consider the temperature profiles along lines that radiate from the array axis ($x = y = 0$). These temperature profiles pass through the gas and rods. They are fairly flat near the array center, but exhibit steeper gradients near the walls. Bowing of the heater rods causes the thermocouples at $z = 0$ to be shifted in the $x$- and $y$-directions by small but random amounts. The rods in the $\gamma$ group are relatively close to the array center, so small shifts in their location will not cause a large change in their temperatures. However, rods in the $\delta, \epsilon,$ and $\zeta$ groups are close to the walls where the radial temperature gradient is steep. As a result, their temperatures are relatively sensitive to...
small location variations. Interestingly, the temperature deviations within the \( \zeta \) group are relatively small. It is possible that the rods in that group are relatively straight compared to that of the other groups. Unfortunately, it is not possible to test that hypothesis because the bowing of those rods were not observed before the experiment was disassembled.

Figure 6 shows that the configuration error within a symmetry group is larger for groups that are nearer the array periphery, because their temperatures are more sensitive to random location variation than those in groups near the array axis. We conclude that measurements made near the array axis are more valuable for assessing the accuracy of simulations than ones near the periphery.

**Numerical Simulations**

**Computational Domain.** Two- and three-dimensional computational meshes representing the experimental apparatus were generated using ANSYS Meshing. Figure 7(a) shows an \( x,y \)-plane of a computational mesh. The outer portion of the plane consists of a 0.25 cm-thick aluminum region, which represents the portion of the enclosure that is inside the locations where temperatures are measured. It also contains regions for the 64 heater rods (magnesium oxide core and Incoloy sheath), and the helium between the rods and enclosure. This mesh was extruded in the \( z \)-direction (normal to the plane of the mesh) to form the three-dimensional mesh.

At the ends of the extrusion, the properties of 0.635 cm-long regions are modified to represent the two stainless steel spacer plates. Figure 7(b) is an expanded view of section 1 from Fig. 7(a), showing the solid and gas regions near the spacer plates. Darker shaded regions show the helium-filled gaps. These gaps are between the spacer plate and enclosure wall (except at the corners where the spacer plates are supported), and between the rods and plate holes. As described earlier, expansion rings between each set of four rods press the rods against the portions of the spacer holes that are away from the rings. The resulting eccentricity of the rods and holes is represented in the mesh as a 45 deg-arc contact surface. The total number of mesh elements in the three-dimensional domain is 1,834,880. For comparison, another mesh was constructed with the rods symmetrically centered within the holes.

Temperature-dependent material properties were assigned to all of the magnesium oxide, Incoloy, stainless steel, aluminum, and helium regions. The emissivities of the anodized aluminum enclosure walls, Incoloy heater rod sheaths, and stainless steel spacer plates were measured. However, after the experiments were completed and the enclosure was reopened, all interior surfaces were found to be coated with a film of vacuum pump oil. The emissivity of the coated surfaces was not measured, but was approximated to be very near unity [26].

In the model, heat is generated uniformly throughout the magnesium oxide, except in the \( z \)-locations within the spacer plates. For the simulation of each experiment, the total heat generation rate is equal to that of the experiment. The outer surfaces of the aluminum region are set uniformly to the average measured temperature of the enclosure walls.

At the top and bottom of the domain (outer surfaces of the spacer plates), the end surfaces of the heater rods and the helium gaps are insulated. Three different types of boundary conditions are applied to the stainless spacer plates. The first is the regional temperature condition, in which the spacer plates are divided into nine regions, which are shown in Fig. 7(a) separated by the vertical and horizontal lines. The temperature in middle region of the top and bottom plates (marked M in Fig. 7(a)) is set to the temperature measured at the center thermocouple for each plate (center \( X \) in Fig. 3). The temperature of all four side regions (marked S) is the value measured by the thermocouple at the side of each plate (\( X \) near the top of Fig. 3). The corner region temperature (marked C) is set to a value that is the average of the measured two or three corner regions for that plate, which was then averaged with the measured enclosure temperature. This second average was used because simulation results show that significant portions of the corner regions are cooler than the location where the temperature is measured. The second type of spacer plate boundary condition is a uniform temperature, in which the area-weighted average temperature for each plate is applied to that plate’s entire outer surface. In the third type of boundary conditions, the outer surfaces of the spacer plates were simply insulated.

Conduction, natural convection, and radiation heat transfer within the domain were simulated using ANSYS/FLUENT. The steady-state momentum and energy equations were solved using a pressure-based solver where the pressure–velocity coupling was achieved using the SIMPLE scheme and discretization was achieved using a second-order upwind scheme [27]. The discrete ordinate model was used to calculate radiation heat transfer. For natural convection, buoyancy-induced flow was generated using gravitational acceleration in negative \( z \)-direction. Temperature-based density was applied to helium for the steady-state pressure measured for each experiment.

**Fig. 7 Computational domain (a) Full \( x,y \)-plane divided into nine middle, M, side, S, and corner, C, regions (b) enlarged view of section 1 from part (a), showing eccentricity of the heater rods**
To check the sensitivity of the mesh, two finer meshes were constructed with 2,111,992 and 4,730,080 elements. Simulations representing experiments I and IX (see Table 2) were performed using all three meshes. The difference between the maximum temperatures for each mesh was less than 0.3 \(^\circ\)C. Hence, the coarse mesh shown in Fig. 7 was used for all presented simulations.

**Simulation Results.** Figure 8 shows simulation results for the rod heat generation rate, gas pressure, and enclosure wall and spacer plate temperatures measured for experiment VII. These simulations employed the regional temperature spacer plate boundary conditions. Figure 8(a) shows rod surface temperature contours. Half of the rods are removed to expose the center of the array. The hottest region is slightly above the array midheight, at \(z = 4.4\) cm. Much of the central rod surface temperatures are fairly uniform, but the temperature exhibits rapid drop offs at the rod tops and bottoms, and on rods close to the walls. Figure 8(b) shows the vertical component of gas velocity at the midheight (\(z = 0\)). The surface is colored according to the gas temperature. It shows that natural convection causes the warm gas near the center to move upward with a maximum speed of around 4 cm/s, and downward along the walls with a peak of around \(-3\) cm/s. The gas moves in rounded-cross section up-flowing and down-flowing jets in between the heater rods.

For experiment VII, the average measured enclosure wall temperature and the maximum measured rod temperature are, respectively, 217.5 \(^\circ\)C and 288.8 \(^\circ\)C, corresponding to a maximum rod-to-wall temperature difference of 71.3 \(^\circ\)C. The simulation shown in Fig. 8 used the measured enclosure temperatures as boundary conditions, and predicted a temperature difference of 71.9 \(^\circ\)C. A simulation performed with no fluid motion gave a temperature difference that was only 0.01\% larger. Another simulation was performed with surface emissivities of 0.75 (reduced from unity), and gave a temperature difference of 88.5 \(^\circ\)C. These results indicate that natural convection contributes little to heat transfer in this system, but radiation and conduction are both important.

The solid lines in Fig. 4 show the temperatures within the \(x, \beta, \) and \(\eta\) rods from simulations that use the regional temperature spacer plate boundary conditions. Even though there are multiple rods in each of these groups, only one line is needed since, due to the precise symmetry of the simulation domain and boundary conditions, the temperatures in all the rods are identical. For both experiments III and VII, the rod temperatures are fairly uniform in the middle 20 cm of the rods and drop off near the top and bottom spacer plates, and the \(x\) and \(\beta\) rods are significantly warmer than the \(\eta\) rods. The simulations show that the heat loss through the outer surfaces of the spacer plates is less than 8\% of the total rod heat generation rate. In the \(x\) and \(\beta\) rods, the location of the maximum temperature is at a larger value of \(z\) for experiment III than for experiment VII. This is caused by natural convection, and is similar to the trend exhibited by the measurements.

Temperature profiles from simulations that use the uniform temperature spacer plate condition are nearly the same as those from the regional temperature boundaries, and so are not included. The dotted lines in Fig. 4 show rod temperature results assuming the spacer plate outer surfaces are insulated. While insulation increases the temperatures of the rod ends, it has little effect on the middle 10 cm of the rods, where the highest temperatures reside. From this, we conclude that the majority of the heat generated within the center region of the rods is transferred radially to the enclosure walls, and not axially to the endplates. To confirm this, simple two-dimensional simulations were performed using the mesh shown in Fig. 7(a). The \(\times, +, \) and \(*\) symbols at \(z = 0\) of Fig. 4 show temperatures within the \(x, \beta, \) and \(\eta\) rods, respectively. The good agreement between the two-dimensional and three-dimensional simulations for both experiments III and VII indicate that the spacer plate thermal boundary conditions have very little effect on maximum rod temperatures, which are located near the rod midheight.

**Comparison Between Simulated and Measured Rod Temperatures**

In Fig. 4, the simulated temperature for all three rods (\(x, \beta, \) and \(\eta\)) in both experiments III and VII are within 3 \(^\circ\)C of the measured values at all four elevations where they are measured, \(z = -17, 0, 17, \) and 29 cm. For the \(\eta\) rods, which are near the array corners, the simulated temperature is below the measured value at \(z = 17\) cm, but above it at \(z = -17\) cm. An additional simulation was performed using an axially varying enclosure temperature that was hotter at the top than at the bottom, based on the measured enclosure temperatures. The resulting simulated temperatures for the \(\eta\) rod are in better agreement with the measurements than curves in Fig. 4, and had little effect on the \(x\) and \(\beta\) rods. This suggests that temperatures of rods in the periphery of the array are more affected by the wall temperature than those near the center. This supports the assessment that rods near the array periphery

![Fig. 8](https://example.com/f8.png)

**Fig. 8** Computational results for experiment VII. (a) Rod surface temperature contours (half of the rods are removed to show highest temperatures) and (b) vertical component of gas velocity in the midplane, \(z = 0\).
may exhibit larger configuration errors than ones near the array center since they are more sensitive to the enclosure temperature profile.

Since the measured enclosure wall and spacer plate temperatures are used as boundary conditions, the simulations essentially calculate the temperature difference between the rods and the enclosure. To compare the simulated and measured temperatures, for all 47 thermocouples in each of the 12 experiments, we calculate the measured rod temperature minus the average wall temperature, $\Delta T_M = T_M - \bar{T}_W$, and the simulated rod temperatures minus the wall temperature, $\Delta T_S = T_S - \bar{T}_W$. Since 21 measurements were excluded based on the modified Thompson tau test, there are 543 measurements and simulation results. Figure 9 is a plot of the simulated versus measured temperature differences. These temperature differences are as large as 72°C. As expected, the simulated temperature difference increases as the measured difference increases, and the correlation appears to be linear.

If the simulations perfectly recreated the measured data, then all of the data would lie along $\Delta T_S = \Delta T_M$, which is shown in Fig. 9 using a thin solid line. The simulated results are scattered in a fairly narrow band above and below that line. The dotted line in Fig. 9 shows the best linear fit to the data, $\Delta T_S = m \Delta T_M + b$, where $m$ and $b$ are, respectively, the slope and intercept found from the least-squares technique. For the results in Fig. 9, $m = 1.02$ and $b = -1.2°C$. The difference between the best fit line and the ideal line $\Delta T_S = \Delta T_M$ is an indication of the systematic differences between the simulated and measured temperatures. The solid and dotted lines in Fig. 9 show that this difference is small compared to the random differences.

The scatter of the results above and below the best fit line is an indication of the random differences between the simulations and measurements. The estimate of the best fit line’s random error, with a 95%-confidence level [26], is calculated as

$$E_{95} = 2 \sqrt{\frac{\sum (m \Delta T_M + b - \Delta T_S)^2}{N - 2}}$$

(3)

The summation is carried out for the $N = 543$ pairs of $\Delta T_M$ and $\Delta T_S$. In terms of Fig. 9, this is the vertical distance above and below the best fit line that statistically contains 95% of the data. For the results in Fig. 9, $E_{95} = 5.7°C$, and dashed lines are placed 5.7°C above and below the best fit line. The region between these two lines contains roughly 95% of the results.

Table 3 reports the best fit slope, intercept, and random error for several simulations and comparisons. The baseline comparison, which is presented in Fig. 9, uses (a) the simulation mesh with rods placed eccentrically within the spacer plate holes, (b) the regional temperature spacer plate boundary condition, and (c) all 543 qualified measurements. The best fit slope, intercept, and random error for the baseline are given in the first line of Table 3. Under ideal conditions, $m = 1$, $b = 0$, and $E_{95} = 0$, and simulations that give parameters that approach these values are judged to be superior to ones whose values are further away. Table 3 shows that simulations using the computational domain with rods placed concentrically (rather than eccentrically) in the spacer holes gave parameters that are slightly more favorable than the baseline. Simulations that use the uniform temperature (area-weighted average) spacer plate boundary condition gave larger random errors than the baseline.

The random differences between the measured and simulated temperatures are affected by inaccuracies of the simulations, configuration errors, and thermocouple measurement errors. The objective of this work is to assess the inaccuracies of the simulations. As discussed earlier, the configuration errors are larger in the array periphery than they are near its center. Table 3 shows that if the outermost rods (all rods in rows A and H, and columns 1 and 8 of Fig. 3) are eliminated from the comparison between the simulations and measurements, then the random differences between the measured and simulation results are reduced to 4.4°C. If only the maximum measured and simulated temperatures are compared, the random error is only 2.0°C, a 63% reduction compared to the baseline comparison. This is not substantially larger than the thermocouple measurement uncertainty of 1.1°C. However, the simulations systematically overpredicted the maximum temperature. We view these latter comparisons to be a better assessment of the uncertainties of the simulation methods than the ones that include all of the rods, because the outer rods are more affected by configuration errors.

**Table 3** Slope and intercept values of regression line for difference boundary conditions and models tested

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Slope, $m$</th>
<th>Intercept, $b$ (°C)</th>
<th>Random error, $E_{95}$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>1.02</td>
<td>-1.2</td>
<td>5.7</td>
</tr>
<tr>
<td>Concentric heater rods</td>
<td>1.02</td>
<td>-1.1</td>
<td>5.6</td>
</tr>
<tr>
<td>Area-weighted average</td>
<td>1.02</td>
<td>-1.5</td>
<td>6.2</td>
</tr>
<tr>
<td>spacer plate temperature</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline (without outermost heater rods)</td>
<td>1.02</td>
<td>-0.1</td>
<td>4.4</td>
</tr>
<tr>
<td>Baseline (maximum temperature only)</td>
<td>0.99</td>
<td>1.4</td>
<td>2.0</td>
</tr>
</tbody>
</table>

**Conclusion**

The goal of the current work is to use experimental measurements to validate CFD simulations of conduction, natural convection, and radiation heat transfer in a configuration that is relevant to a used nuclear fuel assembly within a square basket opening of a vertical storage canister. An experimental apparatus was constructed consisting of an 8 x 8 array of vertical heated rods within a square cross section, helium-filled aluminum pressure vessel. The temperature of the enclosure, heater rods, and spacer plates that hold the rods, were measured using thermocouples with an uncertainty of 1.1°C in 12 experiments for a range of helium pressures, rod heat generation rates, and thickness of insulation surrounding the vessel (to increase the vessel temperature).

Temperatures measured in the rods are affected by both measurement and configuration errors. Configuration errors are caused by small systematic and random deviations from the intended experiment geometry and boundary conditions, such as variations in the heater resistances, rod curvatures, thermocouple locations within each rod, and enclosure wall temperatures. The variation of measured temperatures within symmetrically placed rods was...
used to assess configuration errors. These errors were larger in rods that are close to the array periphery, than for ones near the array center. Measurements with larger configuration errors are less useful for validating simulation results than ones with smaller errors.

ANSYS/FLUENT CFD simulations that model conduction, natural convection, and radiation heat transfer within the rods, spacer plates, enclosure, and helium gas of the experiment were performed. These simulations used the measured spacer plate and enclosure temperatures as boundary conditions. The simulated difference between the rod and enclosure temperatures was compared to the measured differences for all rods and all 12 experiments. The simulations systematically predicted all the trends in the measured data, but had random differences of ±5.7 °C. If the outmost rods are excluded, the random differences are only ±4.4 °C. If only the maximum rod temperatures are considered, the random errors are ±2 °C, but the simulations consistently predict higher temperatures than the measured ones.

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Nomenclature

\[ D = \frac{2}{\pi} \sum \frac{\Delta T_{w}^{2}}{\Delta T} \] measured temperature sample deviation with 95% confidence level

\[ E_{95} = \frac{2}{\pi} \sum \frac{\text{random error of the simulations with}}{95\% \text{ confidence level}} \]

Gr = Grashof number, Eq. (1)

I = insulation thickness

\[ m, b = \text{best fit slope and intercept for} \] \[ \Delta T_{S} = m \Delta T_{M} + b \]

N = number of samples

P = pressure when the experiment is at steady-state

\[ P_{N} = \text{nonlinear pressure when the experiment apparatus is at room temperature} \]

\[ \dot{Q} = \text{assembly heat generation rate} \]

\[ T = \text{average temperature} \]

\[ t_{x,y,z} = \text{coordinate systems with origin at} \]

\[ \text{heater rod array center (Figs. 2(a) and 3)} \]

\[ \Delta T = T - \bar{T}_{w} \] difference between local temperature and average enclosure wall temperatures

\[ \Delta T = \bar{T} - \bar{T}_{w} \] difference between average spacer plate temperature and average enclosure wall temperatures

Subscripts

B = bottom spacer plate

I = index

M = measured

R = revised based on the Thompson modified Tau test

S = simulated

\( T = \) top spacer plate

W = enclosure wall

\( \alpha, \beta, \gamma, \delta, \varepsilon, \zeta, \eta = \) symmetry groups (Table 1)

References


