ABSTRACT

Experiments and computational fluid dynamics/radiation heat transfer simulations of an 8×8 array of heated rods within an aluminum enclosure are performed with nitrogen and helium as backfill gases in both horizontal and vertical orientations. This configuration represents a region inside the channel of a boiling water reactor fuel assembly between two consecutive spacer plates. The rods can be oriented horizontally or vertically to represent transport or storage conditions. The measured and simulated rod temperatures are compared for three different rod heat generation rates to assess the accuracy of the simulation technique. Simulations show that temperature gradients in the air are much steeper near the enclosure walls than they are near the center of the rod array. The measured temperatures of rods at symmetric locations are not identical, and the difference is larger for rods close to the wall than for those far from it. Small but uncontrolled deviations of the rod positions away from the design locations may cause these differences. The simulations reproduce the measured temperature profiles. For nitrogen experiment in horizontal orientation and a total rod heat generation rate of 500 W, the maximum rod-to-enclosure temperature difference is 138°C. The maximum measured heater rod and enclosure wall temperatures 375°C and 280°C, are measured in 2-inch insulated, nitrogen backfill vertical experiment for 1 atm internal pressure. Linear regression shows that the simulations slightly but systematically under predict the hotter rod temperatures but accurately predict the cooler ones. For all rod locations, heat generation rates, nitrogen and helium backfill gases, and apparatus orientations, 95% of the simulated temperatures are within 11°C of the correlation values. These results can be used to assess the accuracy of using simulations to design spent nuclear fuel transport and storage systems.

NOMENCLATURE

<table>
<thead>
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<th>Symbol</th>
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<tr>
<td>Al</td>
<td>aluminum</td>
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<tr>
<td>C</td>
<td>offset distance between inconel sheath and spacer plate surface</td>
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<tr>
<td>Cr</td>
<td>chromel</td>
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<td>g</td>
<td>gravity</td>
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<td>TIG</td>
<td>Tungsten Inert GasArc Welding</td>
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<td>TC</td>
<td>thermocouple</td>
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INTRODUCTION

Light water reactor fuel assemblies (FAs) consist of zircaloy tubes held in square arrays by periodic spacer plates [1]. Boiling water reactor (BWR) FAs vary from 7x7 to 9x9 arrays, while pressurized water reactor (PWR) FAs vary from 14x14 to 18x18. The majority of tubes contain stacked uranium dioxide (UO₂) pellets. The remaining instrument sheath and guide thimble tubes are hollow. BWR assemblies have zircaloy channels around the array of fuel rods.

Spent Nuclear Fuel (SNF) is highly radioactive and continues to discharge heat after removal from the nuclear/power reactor [2]. SNF is stored under water for a period of time to allow its heat generation and radioactive decay rates to decrease. It is then moved to thick-walled casks for dry storage or offsite shipment. In the casks, individual assemblies are supported within square cross-section openings of a basket structure. The region containing the fuel and basket is evacuated and backfilled with helium or another non-oxidizing cover gas. In transport the fuel rods are oriented horizontally. In storage the packages are frequently placed so that the fuel rods are vertical.

The zircaloy cladding provides an important containment boundary and its temperature must not exceed 400°C during normal conditions [3]. Solar heat flux and heat generated by the fuel makes the package hotter than its surroundings [4, 5]. Package designers and operators must calculate the maximum or peak cladding temperature to assure that it does not exceed the allowed limit. The cask thermal dissipation capacity [6] is the fuel heat generation rate that brings the peak clad temperature to this limit. Cask operators can use this capacity to determine how many fuel assemblies may be safely loaded into a cask, and/or how long the fuel must be aged under water in the spent fuel pool before being loaded.

Finite element models of loaded packages are employed to predict cask and fuel temperatures [4, 5]. In the past, computational resources were not available to accurately model the many fuel rods within the multiple fuel assemblies (some rail and truck transport casks have room for up to 21 and 4 PWR assemblies, respectively [4, 5]). The rods and cover gas within each basket opening were therefore replaced with homogenized solid elements with a uniform heat generation rate. Temperature-dependent Effective Thermal Conductivities (ETC) were applied to these elements [4, 7, 8, 9]. They were developed to model the effects of conduction and radiation heat transfer in the directions normal to the rod axes.

Manteufel and Todreas [8] developed an analytical model for one-dimensional conduction and radiation within a rectangular array of heated fuel rods immersed in stagnant gas. They used this model to calculate a temperature-dependent ETC for the region within the fuel assembly, and a conductance model for the thin band between the assembly envelope and the basket walls. This model neglects possible two-dimensional heat transfer effects at the corners, hollow instrument sheath and guide thimble tubes, external channels, and natural convection.

Bahney and Lotz [9] performed two-dimensional finite element simulations of conduction and radiation heat transfer within the fuel assembly/cover gas region. They constructed one-quarter models of several BWR and PWR fuel assemblies. These geometrically-accurate models included unheated instrument sheath and guide thimble tubes, and external channels. The maximum cladding temperature was determined as functions of assembly heat generation rate and basket wall temperature.

A shortcoming of using thermal conductivity models to calculate temperatures within fuel assembly/cover gas regions is that they approximate heat flux at a location based only on the temperature and its spatial gradient at that location. This is not universally appropriate when thermal radiation and/or natural convection effects are significant. Radiant heat flux at a location is affected by temperatures at a distance. Natural convection is affected by the local fluid velocity, which depends on temperatures at other locations. As a result, an effective thermal conductivity that is appropriate for a basket opening whose walls are isothermal may not be accurate for openings with highly non-isothermal walls.

Current computational resources allow the use of numerical models with meshes that accurately include the many fuel rods and unheated assembly components within a cask. Canaan and Klein performed two-dimensional computational fluid dynamics (CFD) simulations of an 8x8 array of heated rods in a uniform temperature enclosure [10], and benchmarked the results using experimental temperature measurements [11]. However, their wall boundary temperatures were much cooler and more isothermal than those expected on the walls of a
transport cask basket opening [6, 12, 13]. Gomez-Araya and Greiner [14, 15] conducted two-dimensional simulations of geometrically-accurate PWR and BWR assemblies within high-temperature isothermal tank openings. Those simulations used the FLUENT commercial CFD package. The simulations determined the conditions when buoyancy induced gas motion affects peak cladding temperature, as well as the sensitivity to cladding surface emissivity and geometric variations.

Venigalla and Greiner [12] and Gudipati and Greiner [13] performed two-dimensional simulations of whole truck and rail transport cask cross sections that included geometrically accurate fuel rods in each basket opening. These simulations also used FLUENT. Simulations that included buoyancy induced cover gas motion gave temperatures that were very close to those from stagnant gas simulations (in which the gas speed was set to zero). This indicates that natural convection does not strongly affect temperatures within horizontal transport cask. Results from these geometrically-accurate simulations were compared with a homogenized fuel model using the Manteufel and Todreas [8] ETCs. The geometrically accurate models predicted lower cladding temperatures and higher cask thermal dissipation capacities than the homogenized fuel models.

If the higher cask thermal dissipation capacities can be confirmed, spent fuel may not need to be aged under water for as long as indicated by the earlier homogenized models before being transferred to dry casks. The computational methods used in the geometrically accurate simulations must be benchmarked against relevant experimental data before it can be used with confidence.

Lovett [16] measured the temperature of an 8x8 array of heated horizontal rods within an aluminum enclosure. Experiments were performed for different gases in the enclosure, and for a range of gas pressures and rod heating rates. These conditions are similar to those of a BWR assembly within a transport cask. FLUENT simulations of the experiments were performed that employed different assumptions regarding the thermal conditions of the endplates that held the heaters [17]. This was necessary because the endplate conditions were not completely documented. For a certain set of endplate assumptions, the simulation results accurately reproduced the experimental results.

Experiments performed by Arya and Keyhani [18, 19] measured the temperature of twelve vertical heated rods within a constant temperature, internally-finned cylindrical enclosure. Measurements were performed with air or helium in the enclosure for ranges of rod heat generation rates and gas pressures. Steady-state three-dimensional computational fluid dynamics simulations of conduction, natural convection and radiation heat transfer within the experiment were conducted to benchmark the simulation techniques [20]. In the computational model, different thermal conductivities were applied to a spacer plate between a plate that held the heaters and one of the enclosure endplates. This was done to model a range of contact resistance between the plates. This was necessary because the experimental endplate conditions were not completely documented. The calculations accurately reproduced the local and average temperatures when a low plate conductivity (corresponding to a high contact resistance) was modeled. These results emphasize that conditions far from measurement locations can affect experimental results. Those conditions must be well documented if they are to be used to benchmark computational methods.

In the current work an experimental facility is constructed consisting of an 8x8 array of heater rods within a square cross-section aluminum enclosure. It models a section of a spent BWR assembly between consecutive spacer plates, and within the assembly channel. The rod diameter, spacing between rods, and distance from the outermost rods to the enclosure wall are all 10% smaller than the dimensions inside the channel of a GE 8x8 BWR assembly [1]. Araya and Greiner [15] performed two-dimensional CFD simulations of natural convection and radiation heat transfer for a horizontal BWR assembly within a uniform temperature basket cell. They showed that the channel surrounding the fuel rods and the gap between the channel and outer basket can be modeled analytically. As a result, only the region inside the channel is modeled in the current experiment.

The test facility can be placed so the rods are horizontal to simulate the conditions in a transport cask, or vertical to simulate storage conditions. The rod and enclosure temperatures are measured for different gases (nitrogen and helium), for a range of rod heat generation rates (1.5, 3.1, 4.7, 6.25 and 7.8 watts/rod) and gas pressures (1, 2 and 3 atm) in the aluminum enclosure. The data from these experiments are compared to three-dimensional simulations including conduction, natural convection and radiation heat transfer within the same domain using the FLUENT CFD code. The goal of this work is to develop methods to quantitatively assess the accuracy of the computational method for a range of boundary conditions. This is done by benchmarking simulation results against data acquired in a facility with well documented boundary conditions.

**EXPERIMENTAL APPARATUS AND PROCEDURE**

**Apparatus**

Figure 1a shows the 8x8 heater rod array held by 0.635 cm thick stainless steel spacer plates and a 2.54 cm thick aluminum enclosure used in the current experiment. Each rod shown in Fig. 1a is a Watlow Inc. tubular heater that is 1.1 cm in diameter and 67.3 cm long. The rods are made from 0.7-mm-thick Incoloy sheath with compressed magnesium oxide (MgO) powder inside. They are nearly straight, but when laid on a flat surface some exhibit gaps from bowing which are as large as 2 mm near the center. Figure 1b shows schematic axial cross section of a rod with nichrome (NiCr) heater coil. The ends of the heater coil are connected to metal pins that are connected to external power leads. When current passes through the rods the heat generation is nearly uniform except
for 3.2 cm (1.25 inch) unheated sections on both ends (i.e. at the location of the connector pins). For the 64 rods, the average and standard deviation of the measured resistances are 4.0Ω and 0.12Ω respectively. The rod surface emittance as specified by the manufacturer is 0.8.

The sixty-four heaters are divided into eight sets with eight rods each in each set. The rods within each set are wired in series. These sets are then wired in parallel to a 1000 W regulated DC power supply (HP 6218B). Experiments are performed for total heat generation rates of Q = 100, 200, 300, 400 and 500 Watts (1.5, 3.1, 4.7, 6.2 and 7.8 watts/rod). The heat generated from each rod is same within a ±6% uncertainty.

The enclosure is constructed by tungsten inert gas (TIG) welding of four 2.54-cm thick aluminum plates. The enclosure interior height and width are 12 cm, with a tolerance of 0.25 cm. The length of the aluminum enclosure is 91.44 cm and its interior width and height are 12 cm with a tolerance of 0.25 cm. Five thermocouple wells are drilled on each enclosure wall for measuring the temperature of enclosure. Each thermocouple well is 2.3 cm deep i.e. 0.25 cm away from the inner surface of the enclosure. All the five thermocouple wells are located on the axial and mid-plane centerlines to measure the temperature gradient of each wall.

Thirty three of the 47 instrumented heater rods have a type-K (chromel/alumel) thermocouple at their mid-planes and fourteen at other axial locations. The type-K thermocouples are constructed by inserting a chromel (Cr) rod into one end that is roughly half as long as the heater rod as shown in Fig. 1b. A thermocouple junction is formed by wrapping an alumel (Al) wire around the end of the chromel rod. The other end of the alumel wire is connected to an alumel pin at the end of the heater. Thermocouple lead wires are connected to the chromel rod and alumel pin. In instrumented heater rods, both the heater and thermocouple are offset from the rod centerline. The heater coil is centered in heater rods that do not contain thermocouples. The positions of the heater coils and thermocouple junctions are not specified by the manufacturer, so their exact location and variation from rod to rod is not known.

Figure 2a is a schematic of the stainless steel spacer plate with 1.15 cm diameter holes, heater rods are in contact with the bottom of the holes in the spacer plate and a tapered open ring with a bolt. A tolerance of 10 mm to the hole allows the heater to be inserted into the spacer plate freely without any friction. The tapered open ring and bolt arrangement is used to avoid any sliding of the heaters when the apparatus is in vertical orientation. Figure 2b shows the schematic of the bolt screwed to the spacer plate with the tapered opened ring, the ring expands when the bolt is screwed against the tapered edge of the ring and push the heaters against the holes in the spacer plates not allowing the heaters to slide.

The heater rod array is slid into the enclosure leaving a 12 cm gap on either side of the array when the array and enclosure centers are at the same axial location. Figure 3a shows an endplate with an O-Ring, two holes for the thermocouple feedthrough/power supply and twelve holes for the bolts. The O-ring is made of Kalrez Perfluoroelastomer with a limit temperature of 315ºC ($400/O-Ring) used for sealing the apparatus for pressure and vacuum experiments. The two holes for the feedthrough's are used for taking the thermocouple and lead wires out of the apparatus to the data acquisition system. After making the connections, endplate is bolted against the enclosure end using the twelve holes on the endplate. Another endplate of the same dimensions, O-Ring and holes are used for the other end of the enclosure, except one hole is used for the thermocouple feedthrough and the other hole is used for a connector tube. The connector tube is used to either backfill the enclosure with the appropriate gas to the required pressure or removing gas from the enclosure and is connected with an atmospheric valve, evacuation valve, oil filter and an evacuation tube connected to the vacuum pump. The connector tube is instrumented with a low pressure and high pressure gages.

Figure 3b shows the gap on the either side of the array inside the enclosure and is mostly used for the connections and storage of the lead and thermocouples wires from the heaters. The thermocouple and lead wires from the heater array are connected to the respective wires on the feedthrough's making a big cluster of wires in the gap leaving very little space.

Figure 4a shows the experimental apparatus without exterior insulation on a hinged test stand in horizontal orientation. Hinged end of the apparatus is the end at which the apparatus is fixed to the test stand, while the other end of the apparatus is called free end. The test stand is altered and built from the chassis of a desk removing the wooden plank from the top. In horizontal orientation, the free end of the apparatus rests on an insulation sheet fixed to the stand. An aluminum plate is bolted to the bottom end of the endplate on the hinged end of the apparatus with an insulation sheet between the endplate and aluminum sheet (white plate shown in Fig. 4a). The aluminum plate is then bolted to an iron cross bar on the test stand which enables the apparatus to swivel and stand in a vertical orientation. Figure 4b shows the experimental apparatus on the test stand in vertical orientation with the hinged and free ends indicated. When the apparatus is in vertical orientation the upper portion of the endplate on the hinged end rests on another iron cross bar which is detachable from the stand. The circles shown in the figures are locations where type-K thermocouple probes (Watlow Insulated thermocouples) are inserted into thermocouple wells in the enclosure. Figure 4c shows the apparatus in vertical orientation with insulation.

Figure 5 shows a schematic axial cross section of experimental apparatus in horizontal orientation with hinged and free ends. The total length of the apparatus is 91.44 cm. The thermocouples in heater rods at mid-plane and other axial locations are at Z = -17.3, 0, 17.3 and 29.2 cm. The gaps between the heater array and the endplates are filled with thermocouple and lead wire connections to the thermocouple feedthrough's.
Figure 6a shows photograph of endplate and external components on free end. The endplate on the free end has two holes for two thermocouple feedthrough's. Ceramic feedthrough (thermocouple wire and power lead wires) with a short tube has high temperature (635°C) limits, whereas the epoxy feedthrough (all thermocouple wires) has a long tube fitting to compensate for it's low temperature (140°C) limits. Figure 6b shows photograph of endplate along with external components on hinged end. The endplate on hinged end has two holes, one for the thermocouple feedthrough and the other for the connector tube.

Figure 7 shows measured average (three measurements) emissivity of inconel sheath from Watlow tubular heater rod and anodized black dye aluminum enclosure samples for different angles (20° and 60° from normal) as a function of wavelength range. Emissivities were measured using a SOC 410C DHR Reflectometer with an uncertainty of ± 0.03 at Sandia National Laboratory. These measured emissivities are used in the CFD analysis for benchmarking measured data All CFD simulation results presented in this work have $\varepsilon_{\text{Enclosure}} = 0.7$, $\varepsilon_{\text{Heater Rod}} = 0.8$.

The apparatus is tested for leak using a helium leak testing device after assembling and fixing to the stand. The leak rate determined from the test is $2 \times 10^{-10}$ cm$^3$/sec.

**Instrumentation**

Figure 8a is a schematic of end view of experimental apparatus showing 64 heater rods (circles), 2.5 cm thick aluminum enclosure walls, 2.3 cm deep thermocouple wells and TIG welding locations. Textured circles are the heater rods that are instrumented with thermocouples. Open circles are the heater rods with no thermocouples. This pattern of heater rod arrangement in the array is chosen to take the advantage of half and quarter symmetry of the horizontal and vertical orientations respectively. Heater columns and rows are labeled 1 through 8 and A through H respectively. The five X's shown are the locations of type-K Watlow grommet-terminal surface thermocouples on the spacer plates. The direction of the gravity vector shows that the orientation of the apparatus is in horizontal orientation. Figure 8b shows a table of z location of the thermocouple for each heater rod texture in fig 8a. Thirty three of the 47 textured heater rods are chosen to have thermocouples at the mid plane (z = 0) for determining the temperature profiles of the heater columns 1 through 8 for horizontal experiments. Fourteen textured heater rods with thermocouples at different axial locations (z = -17.3, 17.3 and 29.2) are chosen to determine temperature profiles of these heaters along with mid plane temperatures. Heater rods with thermocouples at z = -17.3 and 17.3 are same, but inverted while assembling the apparatus to avoid the setup charges from the manufacturer for two heater rods (z = -17.3 and 17.3) instead of one.

When apparatus is in horizontal orientation, the measured temperatures are expected to be nearly equal at pairs of heater rods that are located symmetrically across the plane mid-way (z = 0) between heater rod columns 4 and 5 (Fig. 8a). For example, the temperatures measured in heater rods C4 and C5 (see row letters and column numbers in Fig. 8a) are expected to be nearly the same. Hence the columns in Fig. 9 are labeled 1&8 through 4&5, where 1&8 shows the heater rods from column 1 and 8 combined. Heater rods with thermocouples at different z-locations are not shown. Circles in these columns with 2 indicate that, both the heater rods in the symmetry location are instrumented, 1 denotes for symmetry pair that has only one heater rod instrumented and open circles are shown for the symmetry pair where both the heater rods are not instrumented. For horizontal experiments, maximum temperatures are expected to be above the mid plane due to buoyancy induced gas motion and hence the upper part of the combined columns are all instrumented except two heater rods to fully understand the temperature distribution at these locations. Heater rods with thermocouples at different z-locations are grouped together to determine the temperature profile of a archetypical heater rod in the assembly. Table 1 shows the symmetry groups for horizontal orientation of heater rods with thermocouples at different z-locations for determining the axial temperature profiles. A total of eight symmetry groups are listed in the table R1 through R8. For example, symmetry group R4 consists of heater rods D4 and D5. From Fig. 8a, heater D4 is instrumented with a thermocouple at $z = 0$ and D5 at $z = 29.2$ cm. Temperatures measured from both these heater rods are used to determine the temperature profile of archetypical heater rod R4.

When the apparatus is in vertical orientation, near symmetry is expected across that plane, the plane midway between rows D and E, and the diagonal plane (the planes connecting rods A1 and H8, and connecting rods A8 and H1). Fig. 10a shows the bottom right part of the symmetry of Fig. 8a when the apparatus is in vertical orientation at $z = 0$. For vertical orientation the heater rods may be broken into ten symmetry group. Table 2 shows the name of each group, the heater rods in each, and the name and number of heater rods in each group that are instrumented with thermocouples. The archetypical heater rod for each group is also shown in Fig. 10a. Similarly, for heater rods instrumented with thermocouples at different z-locations are also grouped together as shown in Table 3 to determine the vertical temperature profile of a archetypical heater rod. If the experimental configuration (geometry and boundary conditions) is perfectly realized, and there are no measurement errors, then all the measured temperatures within each symmetry group will be the same.

However, some factors of the experimental configuration are not rigidly controlled and may disturb this symmetry. These factors include non-uniformity of the heater rod spacing (due to heater rod curvature, the enclosure wall temperature, clearance between heater rod and endplate holes, and non-uniformity of the enclosure inner dimensions); the rod heat generation rate (due to differences in heater rod resistance), the heater rod and enclosure surface emittance; as well as variation of the apparatus from vertical or horizontal alignment.
Variations of temperatures within each symmetry group are also caused by random measurement errors. The apparatus was designed so that the heater rods with thermocouples are positioned to measure temperatures of the expected hottest and coldest heater rods, and so that multiple measurements are made within each symmetry group.

The apparatus has a total of 83 thermocouples (47 in the heater rods, 22 in aluminum enclosure walls, 10 on the spacer plates and 4 on the endplates). All the alumel wires from the heater rods and the surface thermocouples on the spacer plate at the hinged end of the apparatus were connected together and a alumel wire from this group is connected to data acquisition to a individual negative input terminal (all the negative input terminals on the data acquisition are connected in a loop) via the feedthrough on the endplate except the four heater rods (Z = -17.32 cm) that are inverted. The chromel wires from the inverted heater rods and the surface thermocouples on the spacer plate are connected to the data acquisition positive input terminals. Similarly, on the free end of the apparatus, the chromel wires from the heater rods, surface thermocouples on the spacer plate are connected to the positive input terminals of the data acquisition system through the ceramic and epoxy feedthrough, while the alumel wires from the inverted heater rods and surface thermocouples are connected together and a single wire from this group is connected to the negative input terminal of the data acquisition system.

Table 4 shows the 72 experiments that were performed in this study for various insulation layers, gases, pressures, apparatus orientation and rod heat generation rates. All 72 experiments are primarily grouped into three categories based on the layers of insulation on the apparatus, i.e., no-insulation, 2.5 cm thick insulation and 5 cm thick insulation.

Experiments in the no-insulation category are performed with the apparatus covered with 2.5 cm thick Fiberfrax insulation sheets on enclosure aluminum walls. Stainless steel endplates, thermocouple feedthrough's and instrument tube are not insulated. Thirty experiments are performed with this setup. All 30 experiments are performed with nitrogen backfill for both horizontal and vertical orientations for 1.2 and 3 atm enclosure pressure and heat generation rates of 100 W, 200 W, 300 W, 400 W and 500 W.

Experiments in 2.5 cm thick insulation category are performed with apparatus covered with 2.5 cm thick Fiberfrax insulation sheets on enclosure aluminum walls, stainless steel endplates, thermocouple feedthrough's and 2.5 cm thick Isofrax insulation blanket on instrument tube. Thirty six experiments are performed with this setup for both helium and nitrogen backfills for both horizontal and vertical orientations for 1.2 and 3 atm enclosure pressures and heat generation rates of 100 W, 300 W and 500 W.

Experiments in 5 cm thick insulation category are performed with apparatus covered with 2.5 cm thick Isofrax insulation blanket on existing 2.5 cm thick insulation Fiberfrax sheets. Six experiments are performed with this setup in vertical orientation for both helium and nitrogen backfills at 1 atm pressure for 100 W, 300 W and 500 W. The 5 cm insulation is used to elevate the enclosure wall temperatures close to 300°C.

**NUMERICAL MODEL**

**Computational Domain**

Figure 11 shows the three dimensional finite volume computational mesh and coordinate system used in this work. Three meshes (coarse, nominal and fine) were created using MSC/PATRAN mesh generator. This domain includes the region between the spacer plates. Since the temperatures in the enclosure aluminum walls are measured at 0.25 cm away from the inner surface, only a 0.25 cm thick aluminum wall is modeled in the mesh domain instead of a 2.5 cm thick enclosure aluminum wall in the apparatus. The dimensions and emissivities given in Apparatus section, and temperature-dependent properties of the indicated materials were applied to the numerical model. The region of the heater rods that protrudes outside the spacer plate, region between the spacer and endplates and localized heater coil are not modeled in the domain (heat is generated uniformly throughout the heater). Variations due to rod curvature are also not included.

Conduction, natural convection and radiation heat transfer within the domain are simulated using the FLUENT commercial computational fluid dynamics (CFD) package (version 6.3.26). FLUENT solves for conservation of mass, momentum and energy equations using a finite-volume method with discretized governing equations. Pressure-velocity coupling is solved using the SIMPLE method. The computational mesh created using MSC/PATRAN is imported to FLUENT and the governing equations are solved with double precision. Steady solver and a second-order upwind scheme are used for the momentum and energy equations. The buoyancy-induced flow is generated by adding gravitational acceleration $(9.81 \text{ m/s}^2)$ in the $-y$ or $-z$ directions for the horizontal or vertical orientation, respectively. The temperature-dependent gas density is included in the natural convection calculation to model buoyancy. Radiation is solved for gray diffuse surfaces using the discrete ordinates method.

Figure 12a shows an end-view of the computational domain with coarse mesh. The spacer plates in the computational domain are divided into nine parts as shown. X’s show the location of the temperatures measured on the spacer plates whereas solid dots show the locations of temperatures measured on the aluminum enclosure walls. Taking advantage of the half and quarter symmetry for horizontal and vertical orientations respectively, the temperatures measured on the spacer plates are applied independently for each of the nine parts. Figures 12b and 12c show the nominal (174,928 elements) and fine (330,167 elements) meshes. All computational results presented in this work use the coarse mesh. Computational results using nominal/fine mesh (not included in this work) are within 0.16°C of the results with the coarse mesh.
Figure 13a shows a schematic of free end of the experimental apparatus with heater rods protruding out of the spacer plate, the wire connections and the gap between the heater and spacer plate. The 3.1 cm unheated end region of the heater is in contact with the spacer and protruding outside the spacer plate. Figure 13b shows a schematic of computational domain on the free end as modeled. Since, the regions between the spacers on the free and hinged ends are only modeled in the computational domain, the rod ends (Insulated Rod Ends) and the ends of the gaps between the spacer and heater rods (Insulated Gap Ends) are insulated. An effective thermal conductivity ($K_{\text{eff}}$) is calculated for the inconel sheath of the heater and the gap between the sheath and the spacer plate as they are modeled as solid elements.

Figure 14a shows a numerical model used for calculating the effective thermal conductivity of the gap between the spacer plate and the inconel sheath. The domain shown has a heater rod surrounded by inconel sheath and a gap between the spacer and sheath (Offset Distance, C). Three domains with different offset distances are used to calculate the effective thermal conductivity. $K_{\text{eff}}$ is calculated for a range of sheath and spacer temperatures. Figure 14b shows effective thermal conductivity versus offset distance. As expected the effective thermal conductivity increases as the offset distance decreases and tends to be infinite when C = 0. In the current work an effective thermal conductivity of 13.87 W/mºK is used for the simulations with C = 0.135 mm.

**Boundary Conditions**

Figure 15 shows the measured thermocouple temperatures (total of 83 thermocouples - placed within enclosure walls, spacer plates and heater rods) versus time for Q = 100 W (1.5 W/rod) with the apparatus filled with helium at 1 atm pressure in horizontal orientation. The initial temperature of all the thermocouples is same as the ambient room temperature around 23ºC. All temperatures increase until a steady state is reached at approximately 25 hours. Then, to acquire temperature data, experiment is continued at a steady state. The total time for the experiment is 28 hours. The data for the 3 hours after steady state is time averaged. Once time averaged data is acquired for each wall thermocouple, the time averaged data from the five thermocouples on enclosure walls are again averaged to obtain the final average enclosure wall temperature. The final average enclosure wall temperature is later used as temperature boundary condition for the CFD model.

**MEASURED WALL AND SPACER PLATE TEMPERATURE MEASUREMENTS**

Figure 16 shows average temperatures on all four enclosure walls as a function of heat load for no-insulation, 2.5 cm insulation and 5 cm insulation experiments. Each of these categorized experiment are explained in Table 3. The maximum average enclosure temperature measured for no-insulation, 2.5 cm insulation and 5 cm insulation experiments are 193ºC, 222 ºC and 280ºC. The average enclosure temperature increases with the thickness of the insulation enclosing the apparatus. Even though each of the experiment category have experiments performed with either helium or nitrogen backfill, horizontal and vertical orientation for different pressures, they exhibit similar average temperatures. For example, a 2.5 cm insulation has a total of 36 experiments performed for both nitrogen and helium backfill, horizontal and vertical orientations and different pressures (1, 2 and 3 atm), the difference between the average enclosure temperatures of all the experiments at 500 W is 11ºC. A rise of 29ºC is observed between the no-insulation and 2.5 cm insulation experiments, which quantifies the heat losses through the endplates when not insulated.

Figure 17a shows the difference between the maximum and minimum temperatures of all the 20 (five on each wall) temperatures measured on the four enclosure walls for no-insulation (Nitrogen, P = 1, 2 and 3 atm, horizontal and vertical orientation) experiments at 100, 200, 300, 400 and 500 Watts. The difference between the maximum and minimum enclosure temperatures increases with Q and are higher for vertical experiments compared to horizontal. This is due to the high temperature gradient in the enclosure walls for vertical experiments due to buoyancy induced gas motion. The temperature differences tend to increase with pressure and are almost identical for pressures at 2 and 3 atm for horizontal orientation and 1 atm for vertical orientation. Figure 17b also shows the difference between the maximum and minimum temperatures of enclosure walls for 2.5 cm insulation (Nitrogen and helium, P = 1, 2 and 3 atm, horizontal and vertical orientation) experiments at 100, 300 and 500 Watts. The 2.5 cm insulation experiments with nitrogen backfill also exhibit the same trends discussed for Fig 17a. For helium, the wall temperature differences are almost identical irrespective of the pressure and orientation. This is due to the absence of buoyancy induced gas motion , because helium has high thermal conductivity. Figure 17c shows the difference between the maximum and minimum temperatures of enclosure walls for 5 cm insulation (Nitrogen and helium, 1 atm, horizontal and vertical orientation) experiments and as discussed above, the temperature differences for helium are lower compared to nitrogen experiments.

Figure 18a shows the average temperature of the spacer plates (averaged temperature of 10 thermocouples, five on each spacer plate) minus the average temperature of the enclosure walls for 100, 200, 300, 400 and 500 Watts for experiments with no-insulation. The solid and dotted lines represent the horizontal and the vertical experiments respectively. Since, the heaters are in direct contact with the spacer plates, the average temperatures are always higher compared to the enclosure walls. The average temperature difference increases with Q, but decreases with increase in pressure. This is due to the buoyancy induced gas motion inside the apparatus (increase velocity). The vertical experiments for 1 atm and 2 atm pressures exhibit higher average temperature.
difference compared to the horizontal experiments except for 3 atm pressure. Further, the decrease in temperature difference is larger from 2 atm to 3 atm than from 1 atm to 2 atm for vertical experiments compared to the horizontal experiments. This is due to the increased gas motion inside the apparatus at 3 atm pressure.

Figure 18b shows the average temperature difference between the Spacer plate and enclosure walls for experiments with “2.5 cm insulation” at 100, 300 and 500 Watts. Unlike the "no-insulation" experiments with nitrogen backfill, all the vertical experiments have larger temperature differences compared to the horizontal experiments (Figure 18b shows that the average temperature difference for 3 atm vertical experiments is lower than 3 atm horizontal experiments). This is because, buoyancy effect tends to decrease as the enclosure wall temperatures increase. For experiments with helium backfill, the average temperature differences are almost identical irrespective of the pressure and orientation of the apparatus. This is due to the absence of buoyancy induced gas motion, because helium has high thermal conductivity. Figure 18c shows the average temperature differences for experiments with "5 cm insulation", the temperature differences with nitrogen backfill are higher compared to helium backfill.

Figure 19a shows the average temperature of spacer plate (5 thermocouples) on the free end minus the average temperature of the spacer plate (5 thermocouples) on the hinged end of the apparatus at 100, 200, 300, 400 and 500 Watts for no-insulation experiments. The average temperatures of spacer plate on the free end of the apparatus are always higher than the spacer plate on the hinged end for both horizontal and vertical experiments. Since, the cross-section areas for buoyancy induced gas motion is larger in vertical experiments compared to horizontal experiments, the average temperature differences are larger for vertical than the horizontal experiments. For Vertical experiments, the average temperature differences increases with Q and are identical for 2 and 3 atm pressure experiments whereas the average temperature difference for 1 atm pressure experiment also increases with Q only up to 300 Watts but remains constant thereafter. This is due to the decrease in gas motion at lower pressures and high rod heat generation rates, where radiation heat transfer tends to overtake convection heat transfer. For horizontal experiments, the average temperature differences are expected to be zero due to symmetry in the apparatus, but increases with Q. This may be due to the experimental and random errors in the apparatus. Figure 19c show the average temperature difference between the free and hinged end spacer plates for 5 cm insulation experiments.

The measured average enclosure wall temperatures are imposed as isothermal boundary conditions to the top, left, right and bottom enclosure walls in CFD simulation model as shown in Fig. 11. Whereas the measured spacer plate ( five on each spacer plate) temperatures are imposed on respective spacer plate grids in CFD simulation model using the horizontal and vertical symmetry of the apparatus as shown in Fig.12. Heat is generated uniformly inside the heater instead of a localized heater coil (NiCr coil). Temperature dependent thermophysical properties are used for all the materials (Aluminum, MgO, Inconel, Stainless Steel Helium and Nitrogen) in CFD simulation model. The values of surface emissivity for enclosure walls and heater rods are taken from their respective measurements shown in Fig. 7.

SIMULATION RESULTS

Figure 20 shows CFD simulation results with nitrogen backfill at 3 atm pressure for 500 Watts with 2.5 cm insulation in vertical orientation. Figure 20a shows enclosure, gas and rod temperature contours at mid-plane between the spacer plates with the maximum temperature at the center of the domain, while Fig. 20b shows temperature contour and velocity vectors in the vertical mid-plane. The velocity vectors in Fig. 20b show that the buoyancy induces an upward gas motion in the vertical mid-plane of the domain and downwards near the enclosure walls. As a result the maximum temperatures are above the domain center in the vertical mid-plane.

Figure 21 shows measured (symbols) and simulated (lines) rod-to-wall temperature difference for a "2.5 cm insulation" vertical experiment with nitrogen backfill of 3 atm pressure at 500 Watts. Results are presented for each symmetry group (described in Table 2) versus x-location of the archetypical heater rod for that group. Ovals enclose data when more than two measurements were acquired at their symmetric locations. The simulations show the rods are nearly isothermal and relatively large temperature gradients exist in the space between the heater rods. All the temperature measurements at groups S1, S2, S3 and S4 are from the heater rods near the enclosure walls, where group S4 comprise of seven heater rods (A4, A5, D1, D8, E1, H4 and H5) with the largest difference between the measurements of 20°C.

As discussed earlier, differences between measurements at symmetric locations are caused by both random measurement errors and uncontrolled aspects of the apparatus (configuration errors). For all no-insulation, 2.5 cm insulation and 5 cm insulation vertical experiments with nitrogen backfill, the largest difference in temperature measurements between symmetric locations is in group S4 near the enclosure wall. For Q = 500 W, P= 3 atm, the difference is 20°C. The differences are significantly smaller at other positions, and they decrease as the heat generation rate
decreases. We note that the simulated temperature profiles exhibit very steep gradients near the walls. As a result, displacements of the near-wall heater rods from their design location of 0.7 to 1.0 mm have the potential to cause large variation in temperatures among symmetry groups.

The rods in symmetry group S9 near x = 5.2 cm (Rods C4 and C5) are near the center of the domain. The measurements from this symmetric pair are very close. Since, the simulated temperature profiles exhibit much smaller temperature gradients in the vicinity of these heater rods than they do near the walls, small position variations of these rods are not expected to cause as large a temperature variation as they would for rods near the walls.

The simulated rod-to-wall temperature difference follows the measured temperature profiles. The simulations over predict the maximum measured temperature difference (in symmetry group S10) by 5°C.

Figure 22a shows measured (symbols) and simulated (lines) rod-to-wall temperature difference for the archetypical heater rods for a "2.5 cm insulation" vertical experiment with nitrogen backfill of 3 atm pressure at 500 Watts. Results are shown for each symmetry group (described in Table 3) versus the z-location (along the length of the heater rod) of the archetypical heater rod for that group. Symmetry group S11 contains heater rods that are near the enclosure walls.

Maximum temperature difference is above the center of the domain due to the buoyancy induced gas motion inside the apparatus as observed in Figure 20. The rods in symmetry group S14 are at the center of the domain and exhibit the hottest temperatures measured. Measured temperatures difference in symmetry group S13 has a symmetry pair for every heater rod in its group as shown in Figure 8a and Table 3. The measurements are too close to identify the difference between them and hence can be seen as a single symbol.

Symmetry group S11 has heater rods near to the two enclosure walls (all four heaters are at the four corners of the heater rod array, figure 8a), where a small displacement in the heater rod would effect the temperature measurement as the temperature gradient from the enclosure wall to the nearest heater rod very steep. The X's shown are the temperature measured on the free and hinged spacer plates. Temperatures of the spacers on the free end are hotter than the hinged end, due to the buoyancy induced gas motion (described in Fig. 19). Also, the enclosure wall and endplate temperatures are affected due to the buoyancy induced gas motion. The temperatures measured at the thermocouple locations near the hinged end are lower compared to the temperatures measured at the locations near the free end.

The CFD simulations accurately predict the temperature measurements at z = 0, 17.3 and 29.2 cm, but, over predict at z = -17.3 cm near the hinged end for the symmetry groups S12, S13 and S14. However, for the symmetry group S11, the simulations under predict at the top and under-predict at z = 0, 17.3 and 29.2 cm and over predict at z = -17.3 cm. This is due the heater rods in group S11 are all near the walls as described earlier.

Figure 22b shows measured (symbols) and simulated (lines) rod-to-wall temperature difference for the archetypical heater rods for a "2.5 cm insulation" vertical experiment with helium backfill of 3 atm pressure at 500 Watts. Since helium has higher thermal conductivity compared to nitrogen, there is no buoyancy induced gas motion. Hence, the hottest temperatures are at the center of the domain.

Figure 23 shows CFD simulation results for a "2.5 cm insulation" horizontal experiment with nitrogen backfill of 3 atm pressure at 500 Watts. Fig. 23a shows enclosure walls, and rod temperature contours and velocity vectors at mid-plane between the spacer plates. The velocity vectors show that the buoyancy induced upward gas motion in the center of the domain and downward near the enclosure walls. The maximum temperatures are above the domain center. Fig. 23b shows the temperature contours at the axial mid plane between the enclosure walls (y-z plane). The maximum temperatures are above the center of the domain.

Figure 24 shows measured (symbols) and simulated (lines) rod-to-wall temperature difference for a "2.5 cm insulation" horizontal experiment with nitrogen backfill of 3 atm pressure at 500 Watts. The temperature difference between each heater rod location and the coolest temperature on the enclosure walls, \( \Delta T = T(y) - T_{WALL,MIN} \), is plotted versus elevation above the bottom enclosure wall, y. The lines show the temperature difference along vertical lines that bisect the rod columns described in Fig. 9. To reduce crowding, the temperature differences from columns 1&8 and 3&6 are shown in Fig. 24a and those from columns 2&7 and 4&5 are shown in Fig. 24b. Ovals enclose data when more than two temperature measurements were acquired from a symmetry pair. As discussed earlier, the difference in temperature difference between the heater rods in a symmetry pair are due to the random measurement errors and uncontrolled aspects of the apparatus (configuration errors). For all the "2.5 cm insulation" horizontal experiments, the maximum deviation in the temperature difference of a symmetry pair is 8.5°C and is significantly smaller at other y-locations. As described earlier for Fig. 21, the simulated temperature difference profiles for the heater rod columns exhibit steep gradients near the enclosure walls.

The maximum temperature difference is at y = 0.8 cm in column 4&5 in Fig. 24b and are near the center of the domain. This is due to the buoyancy induced gas motion as shown in Fig. 23. The difference between the temperature differences of the heater rods at this symmetry location is 0.2°C. Simulations over predict measured temperature data for columns 4&5 and 3&6. CFD simulations predict measured data accurately.

Figure 25 shows measured (symbols) and simulated (lines) rod-to-wall temperature difference for a "2.5 cm insulation" horizontal experiment with helium backfill of 3 atm pressure at 500 Watts. Unlike the nitrogen backfill experiments,
the buoyancy induced gas motion for helium backfill experiments is smaller due to the high thermal conductivity of helium and hence, the maximum rod-to-wall temperature difference is always at the center of the domain (D4 and D5, y = 5.2 cm and 6.6 cm). The simulated rod-to-wall temperature difference follows the measured temperature profiles.

Figure 26 is a plot of the simulated rod-to-wall temperature difference versus the measured value. Results are given for all 47 measured rods, all three heat generation rates, helium and nitrogen backfill and both the horizontal and vertical rod orientations, totally N = 3384 measurement/simulation results. If the simulations modeled the experiment and its measurement errors perfectly, all data would lie on the line marked ∆T_{MEAN} = ∆T_{MEAN}.

Linear regression gives the line marked “∆T_{LR} = 0.97∆T_{MEAN} + 0.8°C.” Systematic errors in the simulation and measurement methods, and in the experimental configuration cause this line to deviate from ∆T_{SIM} = ∆T_{MEAN}. The regression line shows that, on average, the simulations slightly but systematically under-predict the higher temperatures, but accurately predict the lower ones.

The actual measurement/simulation results in Fig. 26, (∆T_{SIM}, ∆T_{MEAN}) for i = 1 to N, deviate somewhat randomly from that line. This is caused by random error in the simulations, experiment and apparatus configuration. The standard deviation of the output describes the vertical deviation of the data from the fit line and quantifies the random errors. It is defined as [21]

\[ S_0 = \sqrt{\frac{\sum_{i=1}^{N} [(0.97\Delta T_{MEAN} + 0.8°C) - \Delta T_{SIM,i}]^2}{N - 2}} \]

For the data in Fig. 26, S_0 = 5.53°C. We therefore expect that 95% of the simulated results are within 2S_0 = 11°C of the linear regression correlation.

CONCLUSION

Experiments and computational fluid dynamics/radiation heat transfer simulations of an 8x8 array of heated rods within an aluminum enclosure are performed with nitrogen and helium as backfill gases in both horizontal and vertical orientations. This configuration represents a region inside the channel of a boiling water reactor fuel assembly between two consecutive spacer plates. The rods can be oriented horizontally or vertically to represent transport or storage conditions. The measured and simulated rod temperatures are compared for three different rod heat generation rates to assess the accuracy of the simulation technique. Simulations show that temperature gradients in the air are much steeper near the enclosure walls than they are near the center of the rod array. The measured temperatures of rods at symmetric locations are not identical, and the difference is larger for rods close to the wall than for those far from it. Small but uncontrolled deviations of the rod positions away from the design locations may cause these differences. The simulations reproduce the measured temperature profiles. For nitrogen experiment in horizontal orientation and a total rod heat generation rate of 500 W, the maximum rod-to-enclosure temperature difference is 138°C. The maximum heater rod temperature 375°C, is measured in a 2-inch insulated, nitrogen backfill vertical experiment for 1 atm internal pressure. Linear regression shows that the simulations slightly but systematically under predict the hotter rod temperatures but accurately predict the cooler ones. For all rod locations, heat generation rates, nitrogen and helium backfill gases, and apparatus orientations, 95% of the simulated temperatures are within 11°C of the correlation values. These results can be used to assess the accuracy of using simulations to design spent nuclear fuel transport and storage systems.

REFERENCES


DOE Commercial Spent Fuel Management Program Office at the Pacific Northwest Laboratory, B-D339-A-G.


Fig. 1. (a) Photograph of 8 x 8 heater array with empty enclosure in the background (b) Schematic axial cut through one rod showing internal components (not to scale).

Fig. 2. System for fastening heater rods to spacer plates (a) Schematic of a part of the spacer plate with four holes of 1.15 cm in diameter, heaters in contact with the bottom of the openings and a tapered open ring with a bolt (b) The bolt screwed to the spacer plate with the tapered opened ring pushing the heaters against the holes.

Fig. 3. (a) Endplate with high temperature perfluoroelastomer (315°C) O-ring, two holes for thermocouple and power feedthroughs (not shown) and twelve holes for the bolts (b) Wire and connectors filled-gap between the spacer plates and the endplate before closure. Feedthroughs can be seen attached to outer surface of endplate.

Fig. 4. Apparatus on hinged test stand without exterior insulation. Circles show the locations where thermocouples enter the drilled thermocouple wells in the enclosure walls. Hinged and free ends are indicated. (a) Horizontal orientation (b) Vertical orientation with no insulation (c) with insulation

Fig. 5. Schematic vertical axial cut view of the apparatus in horizontal orientation. Relative locations of internal components and the z-coordinate are shown. Thermocouples in heaters are located in planes at Z = -17.3, 0, 17.3 and 29.2 cm.
Fig. 6. Photograph of endplates and external components (a) Free end with one high temperature feedthrough (power leads) and one low temperature feedthrough (b) Hinged end with one high temperature feedthrough and a tube for pressure gauge, gas fill and atmospheric valves, evacuation valve, oil filter and evacuation line to the vacuum pump.

Fig. 7. Measured average (three measurements) emissivity of samples of inconel sheath from Watlow tubular heater rod and anodized black dye aluminum enclosure for different angles (20° and 60° from normal) as a function of wavelength range. Standard deviation for three measurements at each wavelength range are shown as error bars. Emissivities are measured using SOC 410C DHR Reflectometer with an uncertainty of ± 0.03.

Fig. 8. (a) End view of experimental apparatus showing 64 heater rods (circles), locations of four spacer plate thermocouples (X’s), aluminum enclosure walls, and the wall thermocouple wells. Textured circles are the rods that are instrumented with thermocouples. The direction of the gravity vector when the apparatus is in horizontal orientation is shown. Columns 1 through 8 and row A through H are labeled (b) Table shows the z location of the thermocouple for each texture used in fig. 8(a).
Fig. 9. Schematic of rod symmetry groups in the mid-plane for horizontal orientation. Columns labeled 1&8 through 4&5, combining the symmetry columns on either side of symmetry line. Circles with numbers show the locations of heaters with thermocouples at mid-plane ($Z = 0$) whereas open circles for heaters with no thermocouples, circles with 1 denotes for only one heater is instrumented with thermocouple among the two heaters for that horizontal symmetry location whereas 2 denotes that both heaters are instrumented.

Table 1 Rod symmetry groups for horizontal orientation for determining the axial temperature profiles of a archetypical heater in the assembly.

<table>
<thead>
<tr>
<th>Symmetry Group name</th>
<th>Rods in Symmetry Group</th>
<th>Rods with TC's in Group</th>
<th>Number of Rods with TC's in Group</th>
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<tr>
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<tr>
<td>R3</td>
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<td>D3, D6</td>
<td>2</td>
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<tr>
<td>R4</td>
<td>D4, D5</td>
<td>D4, D5</td>
<td>2</td>
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<tr>
<td>R5</td>
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<td>R8</td>
<td>H1, H8</td>
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Table 2 Rod symmetry groups for mid-plane ($Z = 0$) temperature profiles for vertical orientation

<table>
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<th>Symmetry Group name</th>
<th>Rods in Symmetry Group</th>
<th>Rods with TC's in Group</th>
<th>Number of Rods with TC's in Group</th>
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<td>S3</td>
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Table 3 Rod symmetry groups for vertical orientation for determining the axial temperature profiles of a archetypical heater in the assembly.

<table>
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<th>Symmetry Group name</th>
<th>Rods in Symmetry Group</th>
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<td>D4, D5, E4, E5</td>
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</table>
Table 4 Number of experiments performed in this study and their categorization

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<tr>
<th>Insulation</th>
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<th>SS - Endplates</th>
<th>Gas</th>
<th>Pressure</th>
<th>Orientation</th>
<th>Heat Load</th>
<th>No. of Experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>No - Insulation</td>
<td>2.5 cm</td>
<td>0</td>
<td>Nitrogen</td>
<td>1, 2 and 3 atm</td>
<td>Horizontal &amp; Vertical</td>
<td>100, 200, 300, 400 and 500 W</td>
<td>30</td>
</tr>
<tr>
<td>2.5 cm - Insulation</td>
<td>2.5 cm</td>
<td>2.5 cm</td>
<td>Nitrogen and Helium</td>
<td>1, 2 and 3 atm</td>
<td>Horizontal &amp; Vertical</td>
<td>100, 300 and 500 W</td>
<td>36</td>
</tr>
<tr>
<td>5 cm - Insulation</td>
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<td>5 cm</td>
<td>Nitrogen and Helium</td>
<td>1 atm</td>
<td>Vertical</td>
<td>100, 300 and 500 W</td>
<td>6</td>
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</table>

Total No. of Experiments = 72

Fig. 11. Three-dimensional finite volume grid mesh and coordinate system

Fig. 12 End view of computational domain divided into nine parts. X's show the locations of the temperatures measured from the experiments on spacer plates and circles show the locations of temperatures measured on the aluminum walls. (a) Coarse mesh (b) Nominal mesh (c) Fine mesh

Fig. 13 (a) Schematic of experimental apparatus on the free end. (b) Schematic of computational domain on the free end.
Fig. 14. (a) Numerical model for calculating effective thermal conductivity for cladding and gap associated with spacer plate. (b) Effective thermal conductivity versus offset distance.

Fig. 15. Measured temperature of all 83 thermocouples versus time with the apparatus filled with helium in the horizontal orientation and $Q = 100$ W and $P = 1$ atm. The enclosure, spacer plate, and rod temperatures are identified.

Fig. 16. Average of measured aluminum enclosure temperatures (20 thermocouples) versus rod heat generation rate for, no-insulation, 1"-inch insulation and 2"-inch insulation experiments.

Fig. 17. Temperature difference between maximum and minimum enclosure temperatures (20 thermocouples) (a) No-insulation (b) 2.5 cm insulation (c) 5 cm insulation.
Fig. 18 Stainless steel spacer average temperature minus enclosure average temperature versus heat load (a) No-insulation (b) 2.5 cm insulation (c) 5 cm insulation.

Fig. 19 Spacer free end average minus hinged end average temperatures versus heat load (a) No-insulation (b) 2.5 cm insulation (c) 5 cm insulation.

Fig. 20 Simulation results for vertical orientation at Q = 500 W, P = 3 atm with nitrogen backfill (a) Enclosure, gas and rod temperature contours at mid-plane between spacer plates (b) Enclosure, gas and rod temperature contours and gas velocity field vectors in vertical mid-plane.
Fig. 21 Measured (symbols) and simulated (lines) mid-plane temperature difference for the vertical orientation. Results for each symmetry group are plotted versus the x-location for the archetypical rod in each group. Ovals enclose data where multiple measurements within a group exist.

Fig. 22 Measured (symbols) and simulated (lines) temperature difference for the archetypical heaters in vertical orientation. Results for each symmetry group are plotted versus the x-location for the archetypical rod in each group (a) nitrogen (b) helium.

Fig. 23 Simulation results for horizontal orientation at Q = 500 W, P = 3 atm with nitrogen backfill (a) Enclosure, gas and rod temperature contours and velocity vectors at mid-plane between spacer plates (b) Enclosure, gas and rod temperature contours and gas contours at the axial mid-plane.
Fig. 24 Measured (symbols) and simulated (lines) mid-plane temperature difference versus y-location for the horizontal orientation. Ovals are used when two measurements were acquired for paired columns. Results from the following symmetric columns are paired together, (a) 1&8 and 3&6 (b) 2&7 and 4&5.

Fig. 25 Measured (symbols) and simulated (lines) mid-plane temperature difference versus y-location for horizontal orientation at $Q = 500$ W, $P = 3$ atm with helium backfill. Ovals are used when two measurements were acquired for in paired columns. Results from the following symmetric columns are paired together, (a) 1&8 and 3&6 (b) 2&7 and 4&5.

Fig. 26 Simulated versus measured rod temperature differences for all 72 experiments performed.