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Author(s): J. Boise Pearson, NASA MSFC
Eric T. Stewart, NASA MSFC
Robert S. Reid, LANL

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Experimental Evaluation of the Thermal Performance of a Water Shield for a Surface Power Reactor

J Boise Pearson¹, Eric T. Stewart¹, Robert S. Reid²

¹*NASA Marshall Space Flight Center, Huntsville, AL 35812 USA*

²*Los Alamos National Laboratory, Los Alamos, NM 87544 USA*

256-961-0078, j.boise.pearson@nasa.gov

Abstract. Water based reactor shielding is being investigated for use on initial lunar surface power systems. A water shield may lower overall cost (as compared to development cost for other materials) and simplify operations in the setup and handling. The thermal hydraulic performance of the shield is of significant interest. The mechanism for transferring heat through the shield is natural convection. Natural convection in a 100 kWt lunar surface reactor shield design is evaluated with 2 kW power input to the water in the Water Shield Testbed (WST) at the NASA Marshall Space Flight Center. The experimental data from the WST is used to validate a CFD model. Performance of the water shield on the lunar surface is then predicted with a CFD model anchored to test data. The experiment had a maximum water temperature of 75 °C. The CFD model with 1/6-g predicts a maximum water temperature of 88 °C with the same heat load and external boundary conditions. This difference in maximum temperature does not greatly affect the structural design of the shield, and demonstrates that it may be possible to use water for a lunar reactor shield.

Keywords: Fission, Reactor, Structural, Shield, Material.

PACS: 28.41Qb, 28.50-k, 29.40-Vj.

INTRODUCTION

As part of the Vision for Space Exploration, NASA plans to return humans to the surface of the moon by the end of the next decade. A critical issue for human presence on the moon is the availability of compact power sources (Angelo and Buden, 1985). Human lunar presence requires power >10 kWt. Nuclear reactors are well suited to meet power generation needs on the lunar or Martian surface.

Shielding is a key component of any surface power reactor system. Several competing concepts exist for lightweight, safe, robust shielding systems such as water, lithium hydride (LiH), and boron carbide. Water offers potential advantages, including reduced cost, reduced technical risk, and reduced mass. Water has not typically been considered for space reactor applications. This is due to the high temperature requirements associated with thermoelectric and thermionic power conversion, and the need for gravity to remove the potential for radiation streaming paths. Experimental demonstration of these concepts, specifically targeted on key technical challenges or questions, is critical to accurate evaluation of their relative merits. LiH shields can be expensive to fabricate, and need to prove adequate radiation tolerance under potential operating conditions. Water shields need to be shown to have adequate natural convection to prevent nucleation or unacceptably high-temperature regions while operating in conjunction with a high temperature reactor coupled to a modern (e.g. Stirling, Brayton, or organic Rankine) power conversion subsystem. The water shield concept relies on predictions of passive circulation of the shield water by natural convection to adequately cool the shield. These predictions need experimental evaluation, especially for shields with complex geometries. NASA Marshall Space Flight Center (MSFC) has developed the experience and facilities necessary to do this evaluation in the Early Flight Fission - Test Facility (EFF-TF).

The EFF-TF was established to provide a capability at MSFC for performing hardware directed activities relevant to multiple nuclear power reactor concepts using non-nuclear test methodology. EFF-TF capability includes fabrication and testing, at both the module/component level, and near prototypic hardware configurations allowing

for realistic thermal hydraulic evaluations of systems. To date the EFF-IF has examined heat pipe reactor systems (Bragg-Sitton, 2005); gas cooled reactor systems (Godfroy et al., 2004), and liquid metal reactor systems.

The objective of this paper is to describe an experimental and analytical demonstration of the thermal performance of a prototypic water shield for a lunar surface reactor. The experiment was performed in earth gravity with full-scale prototypic geometry and heat load, and a CFD model was anchored to this experimental data. The CFD model then predicted shield thermal performance in lunar gravity.

EXPERIMENT DESCRIPTION

This experiment was performed in the Water Shield Testbed (WST) at the NASA Marshall Space Flight Center. The geometry and power requirements for the WST were based on a 100 kWt SNAP derivative reactor design from Los Alamos National Laboratory (Dixon et al., 2006). Figure 1 shows a conceptual layout of this reactor system.

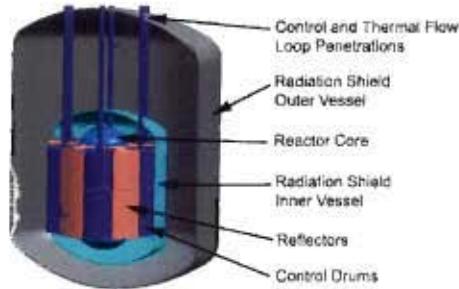
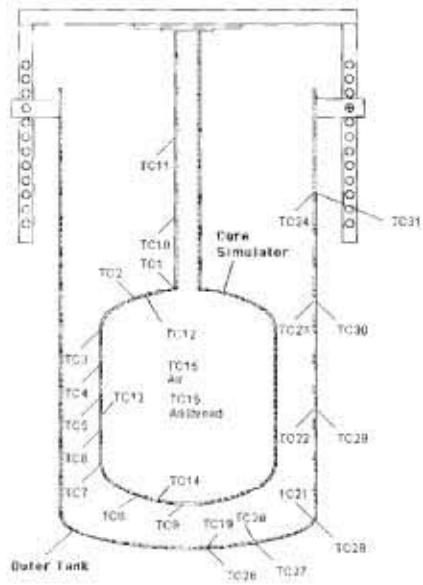


FIGURE 1. Simplified Conceptual Design of a SNAP Derivative Reactor and Water Shield.

The WST consists of an outer tank to simulate the shield's outer vessel, and a core simulator that simulates the radiation shield inner vessel and everything inside it (core, reflector, control drums and coolant manifolds). The outer tank is made from stainless steel, approximately 90 cm diameter and 1.5 m tall. The core simulator is made from 0.64 cm thick aluminum with a 61 cm diameter and 76 cm height, with a 7.5 cm diameter pipe representing vertical penetrations of the shield.



(a) Layout of Water Shield Test Bed.



(b) Core Simulator Suspended Above Outer Tank.

FIGURE 2. Layout of Water Shield Test-Bed with Thermocouple Placement and Numbering.

Figure 2 shows the placement of these two pieces, and the thermocouple locations for each. Note that the thermocouples are staggered azimuthally on the core simulator to place each thermocouple in undisturbed flow. Thermocouples on the outer tank are similarly staggered. A 5-cm thick Styrofoam lid is placed at the top of the outer tank to prevent evaporative cooling losses, but does not pressurize the tank. A band heater is placed on the core simulator pipe, just above the lid, to act as a guard heater and limit heat transfer up the pipe.

Heaters are placed inside the core simulator to provide the internal boundary condition. The heaters are controlled to provide a constant power setting. Heaters are separated in three zones; top dome, barrel, and bottom dome. Total power for this test was 2 kW, with 500 W in each dome and 1000 W in the barrel section. Figure 3 shows the heater placement in the core simulator. The outer tank boundary condition for the test was natural convection in still air.

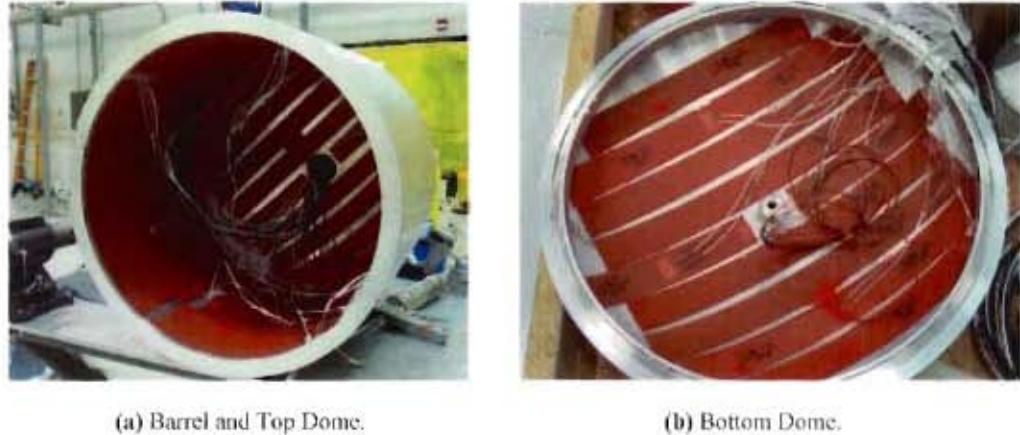


FIGURE 3. Heater Placement in Core Simulator.

EXPERIMENTAL RESULTS

The experiment was run by setting the heater power to 2 kW, and allowing the experiment to come to steady state thermal conditions. Figure 4 illustrates the results of the experiment. Note that the experiment was started from steady state conditions with 1 kW of heater power, not from thermal equilibrium with room temperature. A computer crash at roughly 32 hours caused a short loss of power. The steady state results are used to anchor the CFD model in the 1-g case.

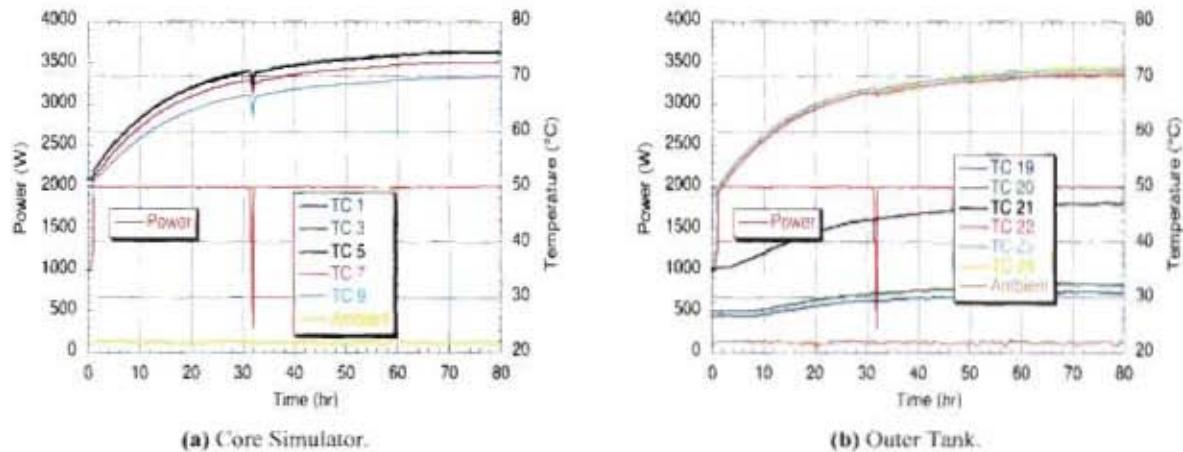


FIGURE 4. Experimentally Measured Transient Behavior of Water Shield.

Thermocouples 3 and 4 consistently show small time-correlated cooling spikes (Figure 5). Data from thermocouple 6 is included in Figure 5 to show 'normal' steady-state behavior. These two thermocouples are located at and just

below the top of the barrel section of the core simulator (see Figure 2). A likely explanation is the repeated formation and shedding of vortices around the transition from the barrel to dome section.

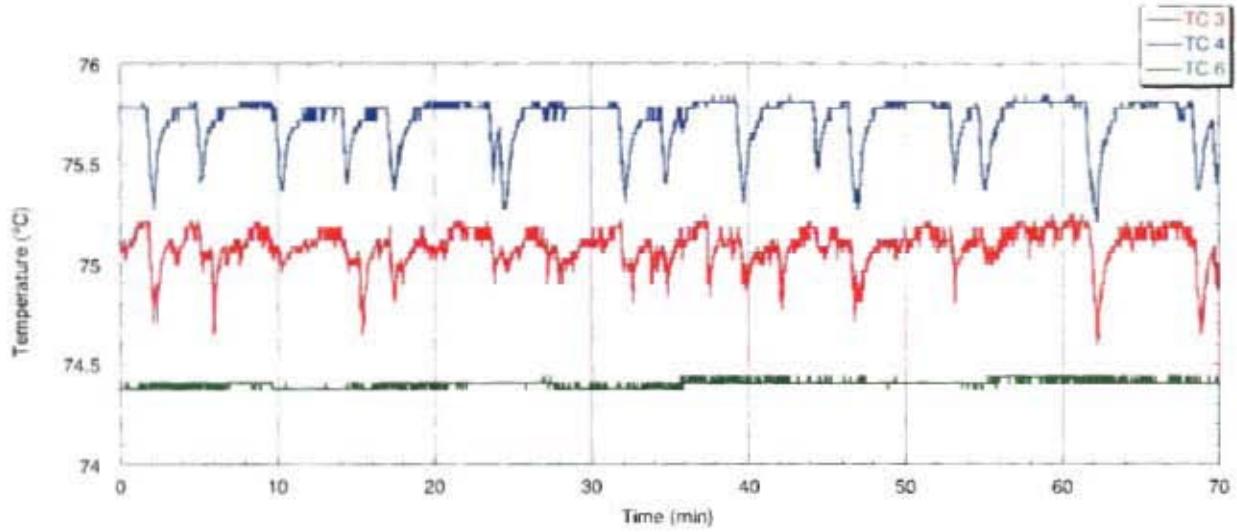


FIGURE 5. Evidence of Periodic Oscillations in Flow.

ANALYSIS

Computational fluid dynamic (CFD) analyses were performed of the water shield test set-up. The long-term objective is for CFD to facilitate the design of water shields on the lunar surface where prototype testing becomes impractical due to the reduced gravitational environment. In the more near term, the current analyses represent the first steps toward achieving this long-term goal.

Computational Fluid Dynamics Code

Software developed internally at Marshall Space Flight Center (Stewart, 2001) was used to perform pre-processing and CFD on a HP Compaq nc4010 laptop. Tecplot (Tecplot, 1999) provided post-processing. The governing equations, in axisymmetric non-dimensional form are:

$$\frac{\partial u_r^*}{\partial r^*} + \frac{u_r^*}{r^*} + \frac{\partial u_z^*}{\partial z^*} = 0 \quad (1)$$

$$\frac{\partial u_r^*}{\partial t^*} + u_r^* \frac{\partial u_r^*}{\partial r^*} + u_z^* \frac{\partial u_r^*}{\partial z^*} = - \frac{\partial P^*}{\partial r^*} + \nu^* \left(\frac{\partial}{\partial r^*} \left(\frac{1}{r^*} \frac{\partial}{\partial r^*} (r^* u_r^*) \right) + \frac{\partial^2 u_r^*}{\partial z^*^2} \right) \quad (2)$$

$$\frac{\partial u_z^*}{\partial t^*} + u_r^* \frac{\partial u_z^*}{\partial r^*} + u_z^* \frac{\partial u_z^*}{\partial z^*} = - \frac{\partial P^*}{\partial z^*} + \nu^* \left(\frac{1}{r^*} \frac{\partial}{\partial r^*} \left(r^* \frac{\partial u_z^*}{\partial r^*} \right) + \frac{\partial^2 u_z^*}{\partial z^*^2} \right) - T^* Gr \quad (3)$$

$$\frac{\partial T^*}{\partial t^*} + u_r^* \frac{\partial T^*}{\partial r^*} + u_z^* \frac{\partial T^*}{\partial z^*} = \alpha^* \left(\frac{1}{r^*} \frac{\partial}{\partial r^*} \left(r^* \frac{\partial T^*}{\partial r^*} \right) + \frac{\partial^2 T^*}{\partial z^*^2} \right), \quad (4)$$

where

$$\begin{aligned}
t^* &= \frac{t}{\Delta t}, \quad r^* = \frac{r}{\Delta s}, \quad z^* = \frac{z}{\Delta s}, \quad u_r^* = \frac{u_r \Delta t}{\Delta s}, \quad u_z^* = \frac{u_z \Delta t}{\Delta s}, \quad P^* = \frac{P \Delta t^2}{\rho_{ref} \Delta s^2}, \\
T^* &= \frac{T - T_{min}}{T_{max} - T_{min}}, \quad v^* = \frac{(v + v_t) \Delta t}{\Delta s^2}, \quad \alpha^* = \frac{(\alpha + \alpha_t) \Delta t}{\Delta s^2}, \quad Gr = \frac{\beta \Delta t^2}{\Delta s} (T_{max} - T_{min}) g,
\end{aligned} \tag{5}$$

The Baldwin-Lomax turbulence model (Baldwin and Lomax, 1978) determines v_t and α_t . An explicit finite difference numerical method approximates the governing equations along with pseudo compressibility to enforce incompressibility. Figure 6 illustrates the computational geometry and the boundary conditions at each boundary. The computational geometry appears shaded but is actually a picture of the computational grid and is indicative of the dense grid spacing. The grid contains 23,368 points. For boundaries 2 and 5 the symbol n is used for the distance normal to the surface. The other surfaces lie on constant r or z lines and the appropriate r or z derivatives are used there.

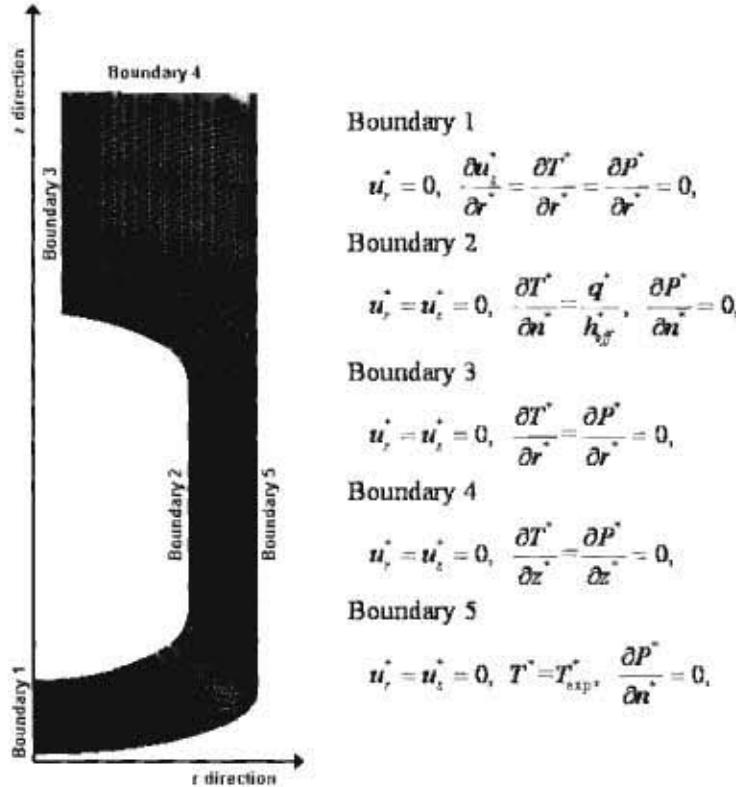


FIGURE 6. Computational Geometry and Boundary Conditions.

CFD Model Anchored to 1-g Test Data

The experimental data used to anchor the CFD model (i.e., determine h_{eff} and T_{exp}) are from the experiment in Figure 4 where the total heat input was 2000 W across the reactor simulator surface (boundary 2) and the bottom of the reactor simulator was 15 cm from the bottom of the outer tank. Two steps were taken to anchor the model to the test data. First, the model was run with the temperatures at TC 1-9 and TC 19-24 fixed to the test data. The steady-state results were used to calculate a local h_{eff} for each point on Boundary 2 (note that this is not the boundary condition specified for Boundary 2 in Figure 6). Second, the model was run using a fixed heat flux on Boundary 2, with the heat transfer coefficients determined in the first step, and with fixed temperatures only on Boundary 5. As expected, the results closely matched the experimental data. Figure 7 illustrates the temperature and velocity magnitude contours for the 1-g case anchored to test data. From the numerical perspective, convergence to a steady state was difficult for these calculations. The more accurate solution may be one of unsteady oscillations, as indicated from

the experimental evidence for vortex formation and shedding in Figure 5. This possibility, along with other numerical questions, has not been fully addressed, and is beyond the scope of this work.

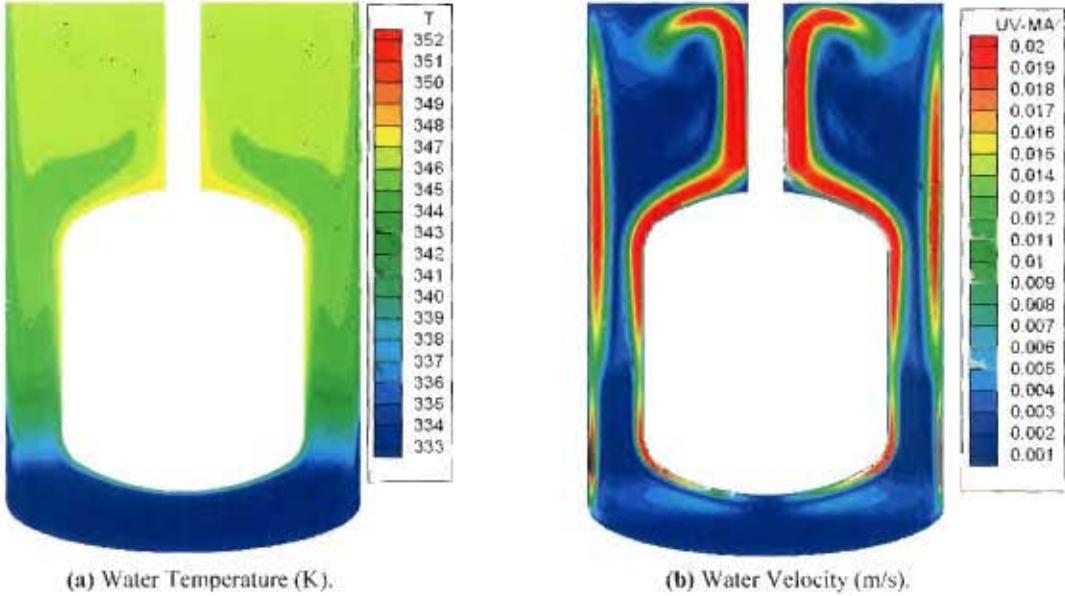


FIGURE 7. Contours for Axi-Symmetric CFD Model of Water Shield for 1-g case (Anchored to Data).

CFD Model Extrapolated to Lunar Gravity

Two modifications were made to the CFD model to predict the behavior in lunar gravity. The first is the obvious reduction of the gravitational acceleration. The second is to scale the heat transfer coefficients that were calculated to anchor the model. Aydin and Guessous (2001) provide insight into the scaling of these coefficients, and suggest scaling by gravity to the $1/5^{\text{th}}$ power. All other aspects of the $1/6$ -g case (e.g., boundary conditions, time step, grid spacing, etc.) are identical to the 1-g case. Figure 8 illustrates the temperature and velocity magnitude contours for the $1/6$ -g case. Note that the scales in Figures 7 and 8 are identical (to aid in comparison) and that this causes the higher temperatures in the $1/6$ -g and higher velocities in the 1-g case to be 'saturated' on that scale.

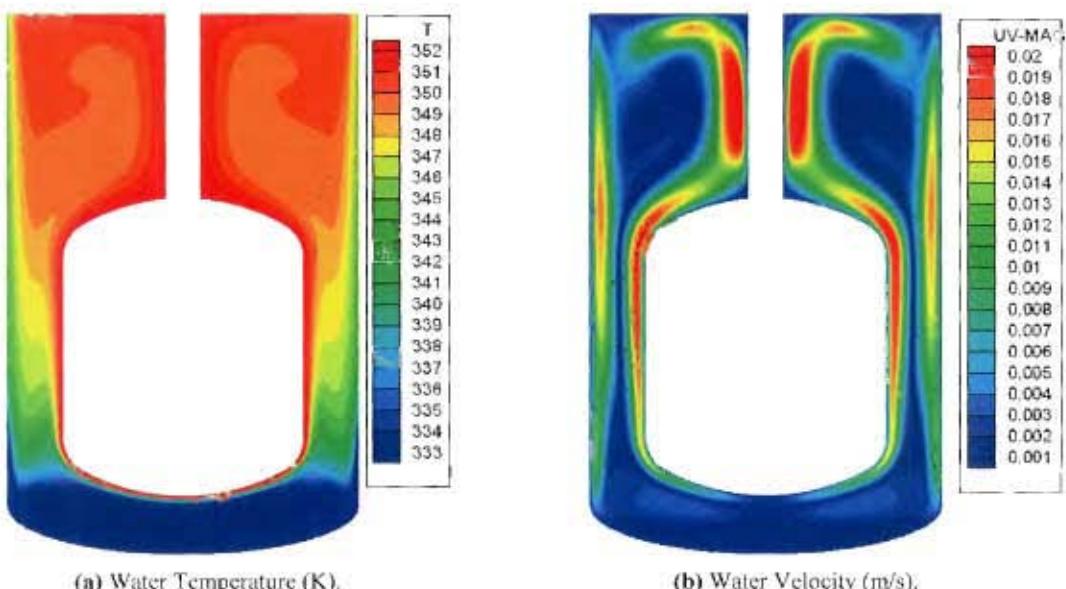


FIGURE 8. Contours for Axi-Symmetric CFD Model of Water Shield for $1/6$ -g Case (Lunar Gravity Prediction).

In both cases, the outer boundary condition is a fixed temperature distribution. This is useful in comparison of the effects of gravity on the flow, but obviously provides no insight into the interaction of the water shield with the real boundary condition (most likely radiation to the lunar environment, either directly or through a radiator system).

Overall, velocities are lower and temperatures higher in the lunar case, as expected. Buoyancy forces in the lunar case are still strong enough to drive a significant circulation of the water, and provide heat transfer through the water shield. Because the boundary condition on the core is a fixed heat flux, the same amount of heat is moved through the shield in both cases. For this heat load, the reduced flow and convective heat transfer drive the core simulator temperatures up to 16 °C higher in the lunar case. Specific temperatures at the thermocouple locations on the core simulator for both cases are tabulated in Table 1. While this increase in temperature is significant, it does not greatly affect the design of the shield as a pressure vessel.

TABLE 1. CFD Predicted Temperatures for 1-g (Anchored) and 1/6-g (Predicted) Cases at the WST Thermocouple Locations.

| TC # | 1-g, anchored T (°C) | 1/6-g, predicted T (°C) |
|------|-------------------------|----------------------------|
| 1 | 74.5 | 79.8 |
| 2 | 74.8 | 80.5 |
| 3 | 74.5 | 80.0 |
| 4 | 75.1 | 81.4 |
| 5 | 74.4 | 81.0 |
| 6 | 73.8 | 82.4 |
| 7 | 72.5 | 83.6 |
| 8 | 72.4 | 88.2 |
| 9 | 69.7 | 84.6 |
| 10 | 73.8 | 78.5 |

This analysis provides a good first look at a correlation between ground testing (in a 1-g environment) and prediction of natural convection in 1/6-g. Several steps can be taken to increase the fidelity of the correlation with the numerical predictions. A fluid temperature rake could be added to help anchor thermal conditions throughout the water, rather than just at the boundaries. Flow visualization could also be used to determine flow patterns that may help to refine the CFD model, and to better understand unsteady flow conditions such as those illustrated in Figure 5.

SUMMARY

Adequate shielding is critical to any surface power reactor system. To date, water has not typically been considered for the shielding of space reactor systems because of temperature requirements associated with thermoelectric and thermionic power conversion. Water based shields become very attractive at the lower temperatures now being contemplated for lunar nuclear power systems. Water shields offer potential advantages, including reduced cost, reduced technical risk, and reduced mass. This work shows an early experimental demonstration of the water shield concept, specifically targeted to answer key thermal management questions. The experiment was conducted at 1-g with full-scale prototypic geometry and heat load. Water temperatures in this experiment reached a maximum of 75 °C. This experimental data was used to anchor a CFD model of the WST. The CFD model was then used to predict the thermal performance in lunar gravity. Predictions showed that the natural convection, while reduced, was still sufficient to keep water temperatures to a maximum of 88 °C. This difference between 1-g and 1/6-g performance would not greatly affect the shield design, and supports the usefulness and validity of using a 1-g test bed to evaluate designs to be used in a lunar environment.

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