MSFC-677

Gravity Scaling of a Power Reactor Water Shield

Robert S. Reid and J. Boise Pearson

[1]NASA Marshall Space Flight Center, Huntsville, AL 35812 USA
256-961-0078, j.boise.pearson@nasa.gov

Abstract. Water based reactor shielding is being considered as an affordable option for use on initial lunar surface power systems. Heat dissipation in the shield from nuclear sources must be rejected by an auxillary thermal hydraulic cooling system. The mechanism for transferring heat through the shield is natural convection between the core surface and an array of thermosyphon radiator elements. Natural convection in a 100 kWt lunar surface reactor shield design has been previously evaluated at lower power levels (Pearson, 2007). The current baseline assumes that 5.5 kW are dissipated in the water shield, the preponderance on the core surface, but with some volumetric heating in the naturally circulating water as well. This power is rejected by a radiator located above the shield with a surface temperature of 370 K. A similarity analysis on a water-based reactor shield is presented examining the effect of gravity on free convection between a radiation shield inner vessel and a radiation shield outer vessel boundaries. Two approaches established similarity: 1) direct scaling of Rayleigh number equates gravity-surface heat flux products, 2) temperature difference between the wall and thermal boundary layer held constant on Earth and the Moon. Nussult number for natural convection (laminar and turbulent) is assumed of form $Nu = CRa^n$. These combined results estimate similarity conditions under Earth and Lunar gravities. The influence of reduced gravity on the performance of thermosyphon heat pipes is also examined.

Keywords: Fission, Reactor, Structural, Shield, Material.
PACS: 28.41Qb, 28.50-k, 29.40-Vj .

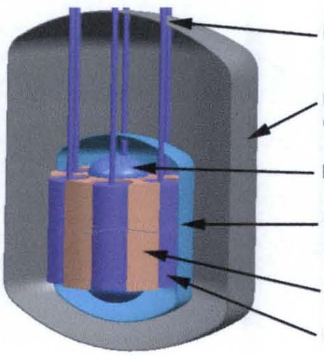
INTRODUCTION

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 at the >10 kWt level (Angelo and Buden, 1985). Nuclear reactors are well suited to meet power generation needs on the Moon or Mars 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 shields need to be shown to have adequate natural convection in reduced gravity present on the Moon to prevent nucleation or unacceptably high-temperature regions while operating in conjunction with a high temperature reactor coupled to a 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. The objective of this paper is to examine the thermal performance of components in a prototypic water shield as a function of gravity. Tests have been performed in earth gravity with full-scale prototypic geometry and heat load, and analytical relations anchored to this experimental data.

SHIELD 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 and the test embodiment. The flight system will likely be made from titanium, but for expedience during test the WST used stainless steel, copper, and aluminum in its construction. Figure 1(a) shows the placement of components internal to the tank and core including the reactor core, reflectors, control drums, and loop penetrations. Figure 1(b) shows the WST consisting of an outer tank, open to the atmosphere, 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. 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 1(b) shows the heater placement in the core simulator. The outer tank boundary condition for the test was natural convection in still air.



(a) Conceptual Drawing of Core and Tank – Less Thermosyphons (Flight).

(b) Water Shield Test Bed Showing Tank and Air Cooled Thermosyphon Array (Test).

FIGURE 1. Test Embodiment Showing Outer Vessel with Thermosyphon Thermal Management Array Compared to Flight Reactor and Water Shield.

One possible embodiment of a shield cooling system would consist of an array of vertically oriented thermosyphons spaced around the WST perimeter. The array would transfer heat from the naturally circulating water to a surface radiator located several meters above the shield. An array of twenty 2-m long water filled thermosyphons were built from 2.54 cm diameter copper refrigeration tube. The thermosyphon evaporators are placed in the water ~2.5 cm from the outer vessel ID. The condenser are coupled to an annular draft cooling system. Figure 1(b) shows the white 2-inch PVC pipe that fits over each thermosyphon condenser. Fans mounted atop the cooling system move air through the annular gap between thermosyphon surface and the PVC pipe.

WATER SHIELD FLOW FIELD CHARACTERIZATION

The underwater video capture in Figure 2 shows a water-filled, heated inner core 0.61-m outside diameter and 0.46-m high (barrel) with a cooled tank diameter of 0.91-m inside diameter. For inside and outside diameters of similar magnitude the geometry can be treated as a two-dimensional enclosure with insulated top and bottom walls. The temperature difference between the barrel and tank is ΔT . Just after power is applied the fluid on the side walls is motionless so heat conducts normal to the wall and forms a hot layer. The energy balance is described by:

$$\frac{\partial T}{\partial t}=\alpha\frac{\partial^2 T}{\partial x^2}, \tag{1}$$

Using scale analysis described in Bejan (1985), early in the transient, $t=0^+$, the thickness of the conduction layer near the heated wall, $x \sim \delta_T$, increases as $\delta_T \sim (\alpha t)^{0.5}$. The fluid begins to rise along the heated wall. For viscous flow, this motion is described by a balance of inertia, friction, and buoyancy forces:

$$\frac{\partial^2 v}{\partial x \partial t} = \nu \frac{\partial^3 v}{\partial x^3} + g\beta \frac{\partial T}{\partial x} \tag{2}$$

For Pr>1, analysis reveals that buoyancy balances friction. At $t=0^+$, $x \sim \delta_T$, the initial vertical velocity scales as:

$$v \sim \frac{g\beta \Delta T \alpha t}{\nu} \tag{3}$$

As heat conducts normal to the wall the thermal layer thickens and buoyant forces carry hot fluid away. A convective term is added to the Equation (1) energy balance:

$$\frac{\partial T}{\partial t} + v \frac{\partial T}{\partial y} = \alpha \frac{\partial^2 T}{\partial x^2} \tag{4}$$

As $t \to \infty$ covection dominates thermal inertia in this balance. Using the Bejan approach $x \sim \delta_T$ and $y \sim H$ and the steady state thickness of the thermal layer near the wall scales as

$$\delta_T \sim H \left(\frac{\alpha \nu}{g\beta \Delta T H^3} \right)^{0.25} \tag{5}$$

A viscous jet will also develop in the region outside the thermal layer. In the viscous jet the buoyancy force in Equation (2) has little effect.

$$\frac{\partial^2 v}{\partial x \partial t} = \nu \frac{\partial^3 v}{\partial x^3} \tag{6}$$

Instead, inertia and viscous forces balance and the layer thickness scales with time $\delta_v \sim (\nu t)^{0.5}$.

As $t \to \infty$, the velocity of the vertical jet then scales as:

$$v \sim \alpha \frac{H}{\delta_T^2} \tag{7}$$

Figure 2 shows a video capture taken with an under water camera of the shield barrel (on right) and tank walls and copper thermosyphons (on left). This capture was taken after the shield had operated steadily for many days, so, barring perturbations by the presence of the video camera, a steady state condition was present. The water and particles are illuminated from above with a flood lamp. Two images are superimposed, taken ~1 second apart, the red arrow shows the path of a flow visualization particle during this interval. Particles away from the heated and cooled regions are nearly stationary during this one second time. High velocity particles are not seen on the tank wall most likely from a combination of unfavorable illumination and a lack of particles in that region.

Figure 2. Overlay capture of flow visualization video over a 1-s interval showing particle movement in flow field. The red arrow denotes typical particle movement in the wall jet.

The particle displacement, represented by the red vector, in the ~1-s interval is 377 pixels. The 2.54-cm diameter thermosyphon in the same view takes 277 pixels. This suggests that if the particle and the thermosyphon are equidistant from the camera that the particle moves at 3.46 cm/s. Table 1 shows the result of the scale analysis for the water shield flow field using Equations 1 through 7. The 3.46 cm/s observed movement compares with the 3.25 cm/s estimate of viscous jet velocity found through scale analysis. The horizontal line normal to the barrel surface marks the approximate boundary of the wall jet. Its thickness, ~0.5 cm, compares with the predicted 0.3 cm thickness by scale analysis.

Table 1. Scale Analysis Results for Natural Convection on Vertical Core Surface Under Various Gravities.

Description	Variable	Earth	Moon	Mars	Unit
Temperature Drop	ΔT	5	5	5	K
Height	H	4.57E-01	4.57E-01	4.57E-01	m
Gravitational constant	g	9.80E+00	1.67E-01	6.25E-01	m/s^2
Thermal expansion coefficient	β	3.40E-04	3.40E-04	3.40E-04	1/K
Thermal diffusivity	α	1.40E-07	1.40E-07	1.40E-07	m^2/s
Kinematic viscosity	ν	1.01E-06	1.01E-06	1.01E-06	m^2/s
Thermal boundary layer thickness	δ_T	1.40E-03	2.19E-03	1.57E-03	m
Velocity of viscous jet	v	3.46E-02	1.41E-02	2.74E-02	m/s
Viscous boundary layer thickness	δ_v	3.14E-03	4.91E-03	3.53E-03	m
Rayleigh number	Ra_H	1.13E+10	1.88E+09	7.06E+09	

FORMULATION OF HEAT TRANSFER SCALING PARAMETERS

Figure 1 shows a drawing of a reactor-water shield assembly. The radiation shield outer vessel is a metal tank 1-m diameter and 2-m tall. The inner vessel that contains the core, also a metal, is 0.6-m diameter and 0.8-m tall. A significant proportion of the heat transfer between the inner and outer vessels is by a natural circulation of water rising on the inner vessel and falling on the outer vessel surface. Conduction and radiation terms are gravity independent, are smaller than the natural convection term, and are not considered here. Volumetric heating of the water by nuclear radiation is small compared to heat transfer from the inner vessel. The pressurized water volume inhibits nucleate boiling onset. For simplicity, only heat transfer from vertical surfaces is considered. A constant heat flux boundary condition exists at the inner vessel surface. The outer vessel will be likely cooled by a heat pipe array producing a mixed boundary condition. To make analysis tractable, a constant heat flux boundary will be assumed to exist on the outer vessel surface.

CRITERIA #1: SIMILARITY BASED ON RAYLEIGH NUMBER

The Rayleigh number describes a balance of buoyant to viscous forces and for a constant heat flux boundary on a vertical surface can be described by:

$$Ra_{H^*} = \frac{g\beta q'' H^4}{\alpha \nu k} \tag{8}$$

where g is the acceleration due to gravity, β is fluid compressibility, q'' is the heat flux at the surface, H is the height of the heated surface, and α, ν, k are the thermal diffusivity, kinematic viscosity, and thermal conductivity of the fluid, respectively. Since fluid properties and geometry of the shield remain similar between the environments the ratio of surface heat flux becomes a simple gravity ratio:

$$\frac{q''_{Earth}}{q''_{Moon}} = \frac{g_{Moon}}{g_{Earth}} \tag{9}$$

with value 1/6. When Rayleigh numbers match so do the Nussult numbers and convective heat transfer coefficients.

CRITERIA #2: SIMILARITY BASED ON TEMPERATURE DROP

Heat flux is proportional to the product of Rayleigh number (to some power) and temperature drop between the walls. The exponent depends on Rayleigh number but is often taken as $n \sim 1/4$ for a laminar regime and $n \sim 1/3$ for a turbulent regime. If temperature drop across the boundary layer is constant on Earth and the Moon, the ratio of the terrestrial and lunar heat fluxes becomes:

$$\frac{q''_{Earth}}{q''_{Moon}} = \left(\frac{g_{Moon}}{g_{Earth}}\right)^{\frac{n}{n-1}} \tag{10}$$

with values 1.82 and 2.45 for the laminar and turbulent regimes, respectively. This relation signifies that to produce a given temperature drop, an Earth-bound shield must operate at higher heat flux than a shield operating in reduced gravity.

GRAVITATIONAL SCALING OF THERMOSYPHON HEAT PIPES

A buried water shield rejects waste heat to a radiator situated above. This geometry favors use of gravity assist heat pipes or thermosyphons for heat transfer between the water volume and the radiator surface. Thermosyphons are subject to several heat transfer limits including the dry out limit, the boiling limit, and the flooding limit. These limits will be briefly discussed here as they relate to gravitational scaling.

For thermosyphons with small working fluid charge and sufficiently high heat flux the condensate flow through the evaporator dries and the wall temperature rises. Correlations typically derive from Nusselt film theory to relate maximum heat transport capability to fluid charge for vertical thermosyphons. The dry out limit strongly depends on fluid charge, and can be largely inhibited given sufficient fill. Further tests and analysis are needed to establish the relation among inclination, fluid charge, and gravity to maximum heat transport capability.

The boiling limit occurs in overfilled thermosyphons with high radial evaporator heat flux. At the critical heat flux, vapor bubbles coelese forming a vapor film at the evaporator wall. This vapor film has poor thermal conductivity and leads to a rapid increase in wall temperature. Gorbis and Savchenkov (1976) developed a correlation for boiling limits in thermosyphons good within ±20 percent:

$$\dot{Q}_{\max} = 0.14 h_{fg} \rho_v^{0.5} \left[\sigma g(\rho_l - \rho_v)\right]^{0.25} C^2 \left[0.4 + 0.012 d \sqrt{\frac{g(\rho_l - \rho_v)}{\sigma}}\right]^2 \pi d L_H \tag{11}$$

$$\text{where } C = A\left(\frac{d}{L_C}\right)^{-0.44}\left(\frac{d}{L_H}\right)^{0.55}\Omega^n \tag{12}$$

with $\Omega \le 35\%$, $A = 0.538$, $n = 0.13$ and $\Omega > 35\%$, $A = 3.54$, $n = -0.37$. Figure 3 shows the effect of gravity on the critical heat flux using Equations 11 and 12. Assuming these relations hold under reduced gravity, at 100 C, there is a factor of ten margin for the thermosyphons operating under Earth gravity and at least a factor of five margin for thermosyphons operating under Moon gravity.

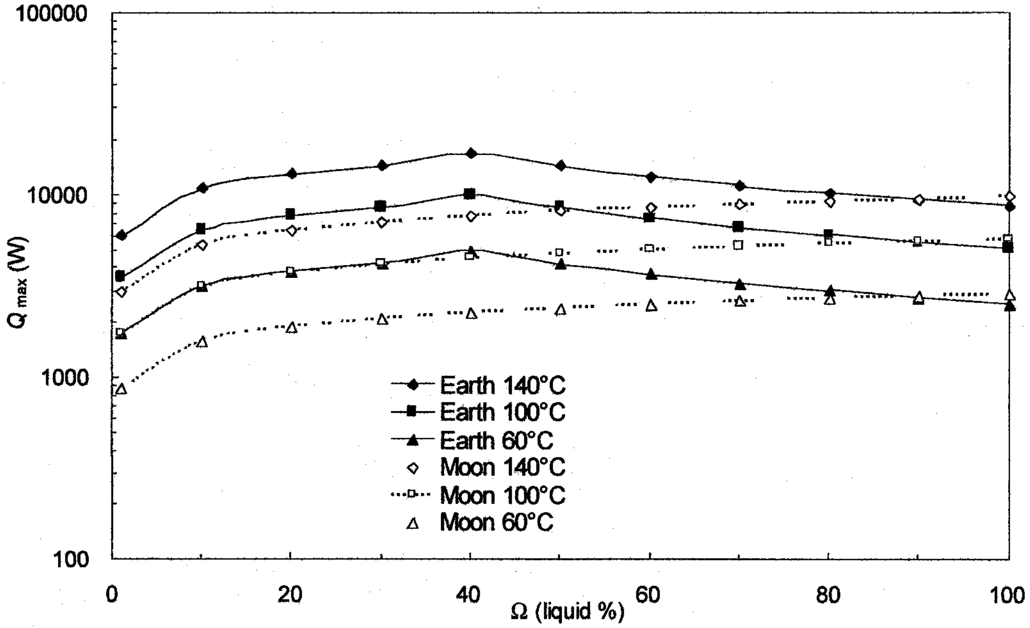


Figure 3. Critical heat flux versus fill fraction at different temperatures and gravities. The design point for a 20 thermosyphon array is 275 W at 100 C.

Gravitational scaling of the flooding limit in a simple wickless thermosyphon is considered here following a treatment by Nguyen-Chi and Groll (1981). Gravity exerts force on a falling condensate film needed to overcome wall friction and shear forces from counter-flowing vapor. The influence of gravity and inclination angle on the flooding limit of a closed two-phase thermosyphon is considered here. The flooding limit as a function of inclination, gravity, diameter, and temperature is given by the Nguyen-Chi Groll correlation:

$$\dot{Q}_{\max} = 0.725^2 \frac{\pi d^{2.5}}{4} \frac{h_{fg}\sqrt{g\rho_v(\rho_l - \rho_v)}}{\left[1 + (\rho_v/\rho_l)^{0.25}\right]^2}\left(\frac{\beta}{\pi} + \sqrt{\sin(2\beta)}\right)^{0.65} \tag{13}$$

Figure 4 plots flooding limit versus angle of inclination, temperature, and gravity using Equation 13. The design point for these calculations is 275 W at 370 K. Assuming this relation holds under Moon gravity, there is at least a factor of 4 margin between the design point and the limit. Ample room is present to fit additional heat pipes around the shield periphery. More margin can be placed in a system design by using more heat pipes having increased diameter.

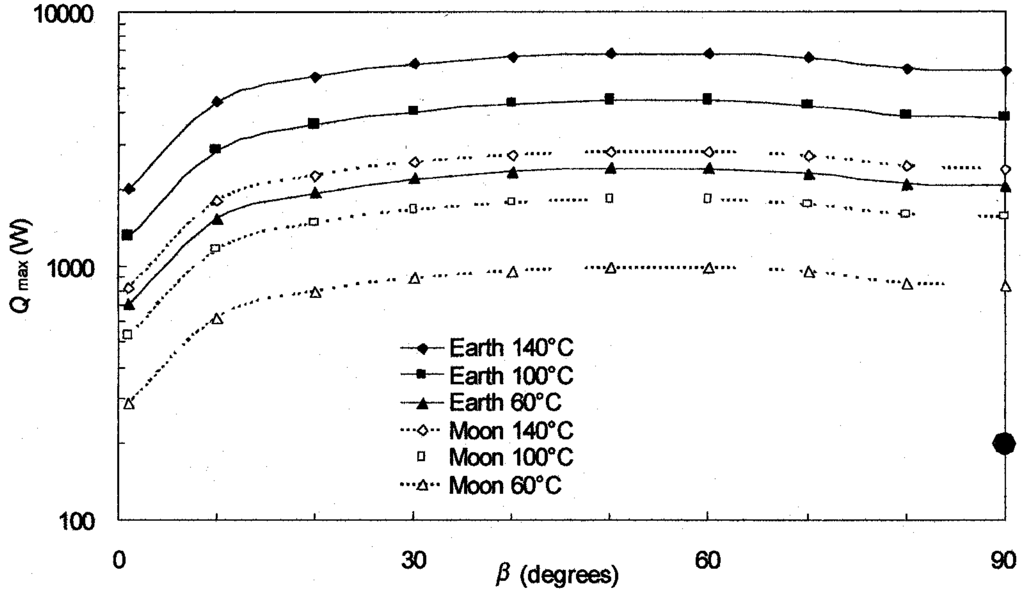


Figure 4. Flooding limit versus angle of inclination for a closed thermosyphon with design point (at lower right).

SIGNIFICANCE OF RESULTS

Table 2 and Figure 5 summarize natural convection scales and the effect of gravity on the various components in a shield operating near 370 K. The relations derived permit rational comparisons between natural convection observed for Earth-based testbeds and what might be expected under reduced gravity conditions. These criteria show that matching all variables simultaneously is not possible. Earth bound test data and numerical predictions will have to be interpreted under a variety of conditions to make reasonable predictions of shield performance under reduced gravity.

TABLE 2. Similarity for natural convection.

	Criteria #1	Criteria #2
Strategy	Match *Ra*	Match ΔT
Constraints	*Ra*, fluid, geometry	ΔT, fluid, geometry
Earth to moon heat flux ratio	Factor 0.16 for all conditions	Factor 1.8 laminar, 2.4 turbulent

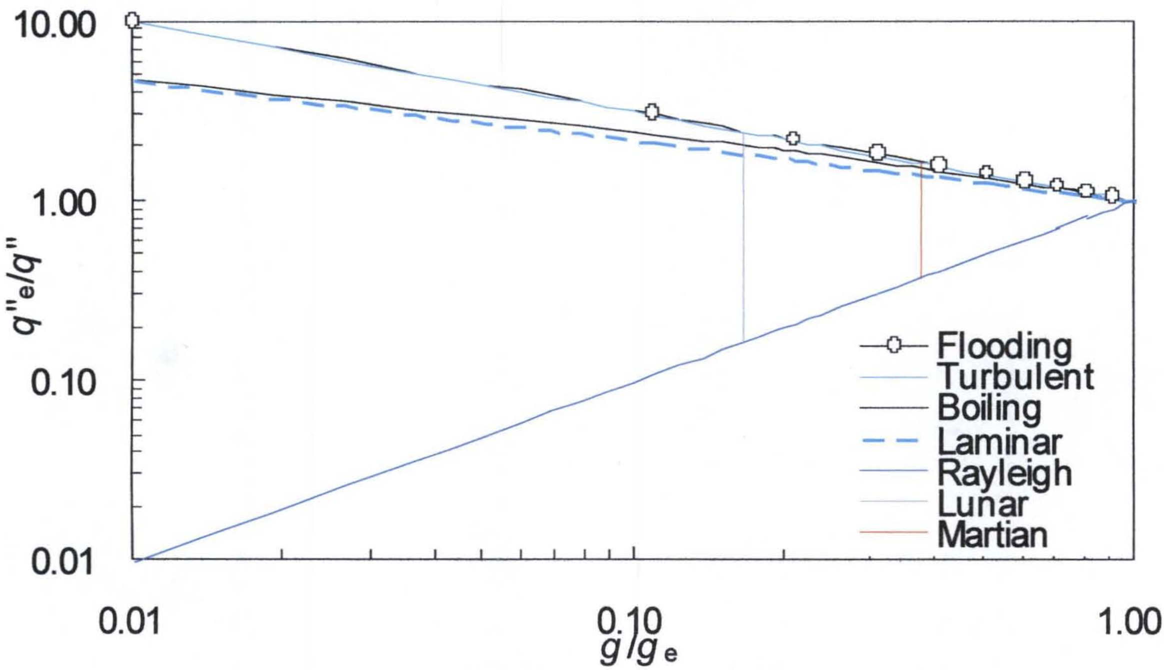


Figure 4. Surface heat flux scales for natural convection at various gravities.

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 the possible effects of gravity on the thermal hydraulic operation of water shield components and requirements for scaling Earth bound tests.

NOMENCLATURE

d = diameter (m)
g = gravitational acceleration (m/s^2)
H = vertical length scale of heated surface (m)
h_{fg} = latent heat of vaporization (J/kg)
k = thermal conductivity (W/m-K)
L = length (m)
n = exponent (1)
Q = heat transfer rate (W)
Ra = Rayleigh number in terms of reference temperature difference (1)
T = temperature (K)
t = time (s)
v = velocity (m/s)
x = distance (m)
y = distance in transverse direction (m)
α = thermal diffusivity (m^2/s)
β = thermal expansion coefficient (1/K)
δ_T = thermal boundary layer thickness
δ_V = viscous boundary layer thickness (m)

ν = kinematic viscosity (m^2/s)
ρ = density (kg/m^3)
σ = surface tension (kg/m-s)

ACKNOWLEDGMENTS

The authors wish to acknowledge the contribution of Pratap Sadasivan in the formulation of the heat transfer scale parameter.

REFERENCES

Angelo, J.A. and Buden, D., *Space Nuclear Power*, Orbit Book Co., Malabar, FL, 1985, pp. 133-157.
Bejan, A., Convection Heat Transfer, John Wiley and Sons, New York, 1985.
Dixon, D., Hiatt, M., Poston, D. and Kapernick, R., "Design of a 25-kWe Surface Reactor System Based on SNAP Reactor Technologies," in the proceedings of *Space Technology and Applications International Forum (STAIF-2006)*, edited by M.S. El-Genk, AIP Conference Proceedings 813, AIP, Melville, New York, 2006, pp. 932-941.
Gorbus, Z. R. and Savchenkov, G. A., "Low Temperature Two-Phase Closed Thermosyphon Investigation," in the proceedings of the Second International Heat Pipe Conference, Bologna, Italy, 1976, pp. 37-45
Nguyen-Chi, H., and Groll, M. "Entrainment or Flodding Limit in a Closed Two-Phase Thermosyphon," in the proceedings of the Fourth International Heat Pipe Conference, Tsukuba, Japan, 1981, pp. 147-162.