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**SOLAR ENERGY
PROGRAM**

HEAT TRANSFER THROUGH A SOLAR POND NONCONVECTIVE ZONE
OF RECYCLED GLASS

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BY

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HEAT TRANSFER THROUGH A SOLAR-POND NONCONVECTIVE ZONE
OF RECYCLED GLASS

BY

DONALD ERNST KETCHUM

B.S., University of Illinois, 1981

THESIS

Submitted in partial fulfillment of the requirements
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ABSTRACT

The heat transfer through a recycled glass/water porous medium is examined experimentally to determine the medium's effectiveness as a nonconvective zone in a solar pond. Temperature distributions within clear bottle or broken glass/water mediums are studied with heated from above, and heated from below orientations. A small solar pond of glass bottles as well as a numerical simulation of a glass sphere solar pond are also investigated.

Results of the experimental study show that convection was not suppressed by using bottles during bottom heating and indicate that stagnation will only occur with very small glass fragments. The computer simulation further indicates that even with perfect transmittance through the medium, pond efficiency will be far less than for a salt gradient pond. The small pond tests show no temperature gradient (indicating little stagnation), show little radiation transmittance through the medium (less than 10% for a .4 meter pond), and confirm the conclusion that a glass bottle or broken glass/water medium is unsuitable as a solar pond nonconvective zone.

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NOMENCLATURE

C_p	Specific Heat	W-hr/kg-K
d_g	Average Glass Thickness	m
d_p	Glass Particle Diameter	m
g	Gravitational Acceleration	m/s^2
H	Bed Depth	m
k	Permeability (See Eqn. 1)	m^2
ΔT	Temperature Across Bed Depth	$^{\circ}K$
q	Heat Flux	W/m^2
R	Conductance	$^{\circ}C/W$
α	Thermal Diffusivity	m^2/s
β	Coefficient of Thermal Conductivity	$^{\circ}K^{-1}$
ϵ	Porosity (Void Fraction)	Unitless
λ	Thermal Conductivity	W/m-K
μ	Viscosity	kg/m-s
ρ	Density	kg/m^3
η	Efficiency	%
ν	Kinematic Viscosity	m^2/s
Nu	Nusselt No. (See Eqn. 3)	Unitless
Pr	Prandtl No. (See Eqn. 2)	Unitless
Ra	Rayleigh No. (See Eqn. 4,5)	Unitless
Ra_{Cr}	Critical Rayleigh Number	Unitless
f	Subscript for Fluid	
m	Subscript for Medium	
g	Subscript for Glass	
p	Subscript for Heater Plate	

INTRODUCTION

This paper considers the heat transfer through a porous medium of recycled glass and water. Its main intention is to determine if such a medium will effectively serve as a non-convective zone in a solar pond.

The steady state solar pond has been described in [1] and [2], and is illustrated in Figure 1. The pond's blackened bottom absorbs penetrating sunlight, and heats water at the bottom of the pond. A stagnation mechanism stops this warm water from rising, keeping the bottom hot (up to 90°C), while the top surface remains near ambient temperature.

A solar pond model has three zones; two convective and one non-convective. The upper convection zone, located at a pond's surface, is at a constant temperature close to the air temperature. This zone is caused by thermal cycling and wind action. The lower convective zone stores heat and serves as a heat transfer medium. Typically the heat exchanger in this zone will power space heating or hot water equipment. The ground insulates the lower convective zone, causing heat to be removed either through the heat exchanger or by passing upward through the pond.

The non-convective zone restricts the heat flow between the lower and upper convective zones. This zone of water should act as a good insulator. For example, a one meter layer of stagnated water insulates as well as 6 cm of styrofoam.

There are three methods currently used to suppress stagnation in this zone. They are a salt gradient (the most common), viscous

Figure 1. The Solar Pond

gels, and stratified membranes. There are problems with each of these. Salt spilled from a pond can kill vegetation and accelerate corrosion. Gels and membranes tend to be expensive.

Recycled bottles or broken glass placed in this zone might prove an efficient stagnation mechanism. Glass is inexpensive and will not adversely affect the environment. If the glass is ground into very tiny pieces, any fluid flow will be stagnated, but the more glass surfaces within a pond, the more reflections, and so the less energy transmitted to the pond bottom. This report examines whether convection can be suppressed at a bottle size that allows adequate energy transmittance.

Considerable research investigating glass-water porous media convection behavior is cited in [3]. Most investigations, however, have been limited to spherical particles. Their results are directed toward the chemical and geothermal fields. Other papers have been published studying rectangular enclosures [4,5] and stratified membranes [6], that might approximate our recycled glass case. There are no reports (to our knowledge) describing this situation of irregular glass shapes.

Our method of investigation includes both a numerical simulation and an experimental study. The numerical simulation examines a solar pond with glass spheres with an estimated level of convection. The experimental study examines bottle or broken glass/water mixtures heated from above and below. Heat fluxes comparable to those of a solar pond ($200\text{--}500 \text{ W/m}^2$) are used. These tests provide estimates of effective thermal conductivity for both heating arrangements.

BACKGROUND

Study of natural convective heat transfer in a porous medium begins with a summary of the basic parameters in the problem. The first of these, the porosity or void fraction (ϵ), is the volume fraction of liquid in the bed. The permeability (k) is defined in [7] as a measure of how easily fluids pass through the medium under the influence of a driving pressure. For heated from below porous media, that driving pressure arises from the warmer, less dense, liquid trying to rise up through the bed. The Blake-Kozeny equation

$$k = \frac{\epsilon^3 d_p^2}{150 (1-\epsilon)^2} \quad (1)$$

empirically estimates the permeability through a bed of spherical particles of diameter d_p . The Prandtl number (Pr),

$$Pr = \nu_f / \alpha_m, \quad (2)$$

is a measure of how rapidly momentum is dissipated compared to the rate of heat diffusion through a fluid. Since the Prandtl number is about 10 times higher for water than air, and because this number plays a part in the heat transfer through the medium, we restrict our references to those with water as the fluid.

The Nusselt number and the Rayleigh number are the two nondimensional groups that best characterize the heat transfer behavior through a porous medium. The Nusselt number (Nu) is the ratio of the energy transport by convection and conduction. Defined by

$$Nu = qH/(\lambda\Delta T) = \frac{q_{\text{below}}}{q_{\text{above}}}, \quad (3)$$

The Nusselt number can be regarded as the ratio of the heat transfer through a medium heated from below to the heat transfer when heated from above (with pure conduction).

The Rayleigh number, (Ra) the ratio of the buoyant and viscous forces in the medium, is defined by

$$Ra = \frac{g\beta\Delta Td^3}{\nu\alpha} \quad (5)$$

where d is the distance between membranes. If there is a relatively large amount of glass surface in the medium (making viscous forces high) or if there is a small temperature difference across the bed (creating low buoyancy forces), the Rayleigh number is low. At low Rayleigh numbers, the viscous forces are dominant, convective flows are suppressed, and heat is transferred through the medium by conduction alone.

Above a critical Rayleigh number (R_c) convection is induced. Various studies (i.e., Buretta and Berman [8], Katto and Masuoka [9], and Elder [10]) have estimated R_c at about 39. Seki, Fukusako, and Ariake [11] explain that with the onset of free convection, thermal boundary layers form at the top and bottom boundaries, forming strong temperature gradients there, while the interior of the porous bed is isothermal. Fluid will flow in cellular patterns, and convective heat transfer occurs. The non-dimensional heat transfer (Nu) then increases with increasing Rayleigh number. This correlation, illustrated in

Figure 2, has been well documented.

We approximate heat transfer through a recycled glass/water medium by three methods. The first is by using Nu vs. Ra correlations from the glass sphere reports by Buretta and Berman [8], Katto and Masuoka [9], and Saki, Fukusako, and Ariake [11] in a solar pond numerical simulation. The second method, from Heitz and Westwater [5] and Catton [4], considers the convection in square cells of sizes comparable to the bottle sizes. The final method estimates the glass as an equivalent stratified membrane solar pond. The basis of this method is Hull [6]. Calculations for the last two methods are presented in Appendix F.

Figure 2. Nusselt vs. Rayleigh Number
Glass Sphere/Water Porous Medium

NUMERICAL SIMULATION

A recycled glass/water solar pond is simulated using a modified version of the model by Newell [12]. The model assumes one dimensional, transient heat transfer through the pond. The pond is divided into several nodes. Using a finite difference formulation, an energy balance is performed at each node. A time step of between 1 and 1/100 day is used. Bottom reflectance and ground properties are constant and defined internally. Pond properties are functions of temperature, including the corrections made for viscosity and thermal expansion coefficient as calculated in [3].

Solar radiation and ambient temperature have been curve fit to weather data as sine functions. The numerous glass/water interfaces have not been considered in determining the sunlight transmitted through the pond. The pond simulation will then give high efficiency estimates.

The program requires the following inputs: 1) pond depth, 2) void fraction, 3) expected Nusselt number, and 4) a constant work extraction rate. The pond depth has been set at 1.5 and 3.0 meters. The simulation has considered the case of glass spheres only. Assuming the spheres are uniformly packed, Muskat [7] examines the ideal packing arrangements as cubic with $\epsilon = .4764$ and rhombohedral with $\epsilon = .2595$. We have examined these two void fractions in the simulation.

The pond is assumed to be stagnant, so we approximate the effective conductivity as the product of the Nusselt number and the stagnated conductivity. We varied the parameter from 1 to 3. Finally, work extraction rates of 0, 10, and 30 W/m² were investigated.

The pond is initially set at a uniform temperature of 10°C on January 1. After the simulation ran for one year, Carnot efficiencies are calculated for each month. The temperature profiles for January and July are also output. The final output of the program is a semi-annual estimate of the maximum sphere diameter to allow the pond to function at the estimated Nusselt number. These calculations are based on the glass sphere/water papers mentioned in the last section.

EXPERIMENTAL STUDY

Apparatus

Three types of tests are performed in the experimental study. The first two types consider glass bottles or broken glass added to an insulated cylindrical container of water, heated from top or bottom. The last test situation considers an actual small solar pond filled with bottles.

The basic apparatus for the top and bottom heating tests is shown in Figure 3. Glass and water are placed in a cylinder with thermocouples randomly placed throughout the medium. This chamber is heated from one end and cooled from the other. The heater is powered by a variable dc power supply. Noting the current from the power supply, and the resistance of the heating plate, we can calculate the heat flux through the medium. The heater, along with the rest of the chamber, is surrounded by several centimeters of insulation. A cooling jacket, acting as a heat sink, is positioned at the other end of the chamber. Tap water runs through this jacket. The thermocouples are monitored by a Fluke model 2190A digital thermometer. From these temperature readings, we can analyze the heat flow in the medium.

The bottles used in the tests are described in Table 1 and shown in Figure 4. The dimensions reported are the average values of a twenty bottle sample. The average glass thickness is .31 cm. The bottles are of clear glass and the glass were assumed to have the same physical properties as common glass. The broken glass tests use fragments from these bottles.

The bottle tests are run in the chamber shown in Figure 5. The glass/water medium is placed in a chamber 24 cm in diameter and 33

Figure 3. The Experimental System

	<u>Bottle</u>	<u>Height (cm)</u>	<u>Width x Depth (cm)</u>	<u>Volume (cm³)</u>
I	Rectangular	12.7	5.1 x 2.5	42.7
II	Irregular	12.7	6.4 x 3.2	54.4
III	Medium Cyl.	9.2	3.7 Dia	25.5
IV	Small Cyl.	6.7	2.5 Dia	11.0
V	Large Cyl.	11.1	4.4 Dia	36.8

Table 1. Bottle Sizes

Figure 4. The Bottles

Figure 5. The Test Chamber

cm in height. This chamber is housed within a plastic can with a cooling jacket in the bottom and a heating plate as a lid. Twenty .16 cm iron-constantan thermocouples are placed throughout the medium. The thermocouples pass out of the medium through four rubber stoppers in a .6 cm thick aluminum disk that interfaces the medium and the cooling jacket. Fixed with glues and sealants 3 cm above the bottom of the plastic drum, this disk forms the cooling jacket. Water circulates through the space by entering through a 1.3 cm diameter tygon tube and plastic nipple in the center and exiting through two similar tubes.

The lid of the can is a heating plate sandwiched between two plastic plates. The heater is a 24 cm diameter aluminum disk, 1.3 cm thick. Four concentric troughs have been machined into the disk, and a length of heating tape run through them. A thin sheet of Mylar separates the heating plate from the porous medium for electrical insulation. A rubber gasket, providing a seal between the heater and the can, and threaded rods holding the assembly together, allow the apparatus to be flipped over for either top or bottom heated tests. About 10 cm of fiber glass insulation is wrapped around the can to provide one dimensional heat transfer through the medium.

The broken glass tests are conducted in a smaller chamber than the bottle tests. The glass fragments are placed in a 4300 ml Pope Lab Grade Dewar model 8642 (see Figure 6). These tests use an immersable plastic heating tape, spiralled within a plexiglas brace that can be set above or below the glass/water porous medium. A cooling jacket can be placed above or below the medium. Ten thermocouples are located throughout the porous medium.

Figure 6. The DEWAR Test

The small scale solar pond tests (Fig. 7), are performed in a galvanized steel tank 91 cm in diameter by 61 cm deep. A blackened sheet metal bottom can be moved up and down to allow a variable pond depth. A pyranometer is positioned on the center of the bottom plate to record the solar radiation at the pond bottom. Another pyranometer outside of the tank reports the radiation incident to the pond surface. The tank is wrapped with 18 centimeters of fiber glass insulation and sits on a bed of several centimeters of insulation. The tank is filled with bottles and six copper constantan thermocouples are placed at different depths toward the center of the tank to reduce the influence of any side wall effects.

Procedure

Before beginning the testing, it was necessary to perform some tests on the apparatus to estimate the actual heat fluxes that the porous mediums would receive and effectiveness of the insulation.

Heater efficiencies for the heated from above tests were found by filling the equipment with water alone, recording the induced temperature gradient, and calculating a heat flux knowing the thermal conductivity of water. For the heated from below tests, no heat sink was used. The heaters were turned on and a bulk temperature measured every few hours. The specific heat of a material is by definition the amount of thermal energy required to raise the temperature of a given mass a specified amount within a specified amount of time. For these tests, we knew the mass, specific heat, and temperature of the water at each time interval, and, therefore, could calculate the heat input and the

Figure 7. The Test Tank

heater efficiency. In the insulation estimates, the containers were filled with hot water, and monitored for temperature as they cooled down.

The water was allowed to set for approximately a half hour to deaerate before being poured into the test chambers. Care was taken in preparing the bottle/water mediums to make sure all air bubbles were removed from the bottles. Thermocouple positions were recorded in cylindrical coordinates. The number of bottles was also recorded for each case.

For broken glass tests, the dewars were filled with broken glass, and the volume of the fragments marked. The glass was then removed, and the volume found by filling that amount with water from a graduated cylinder. The water was next removed, the glass replaced, and the water required to saturate the medium was recorded. These measurements allowed us to calculate a void fraction.

The power input was regulated by a variable resistor in series with the power supply. The resistance of this device was set at a different level to produce a range of heat fluxes in the tests.

Preliminary tests were also performed to estimate the length of time needed for the temperature gradient in the porous medium to reach steady state. Based on those tests, the general procedure was to allow a newly filled test set-up to sit for at least 24 hours with a relatively low heat flux before recording the temperatures. The power setting would then be increased and the temperatures would not be taken for at least another 12 hours. We believed these precautions to be conservative and adequate to ensure only steady state conditions were being observed.

RESULTS

Numerical Analysis

The numerical simulation generated a host of data, the results of which are graphed in Figures 8 thru 10 and Figures 16 thru 22 in Appendix B. Figure 8 shows the temperature difference across a stagnated pond of glass spheres varies only slightly with void fraction. The Carnot efficiency of the pond is shown to decrease rapidly with extraction rate in Figure 9. The calculated maximum sphere diameter to sustain a degree of convection associated with a certain Nusselt number, is shown in Figure 10 to increase with Nusselt number.

The figures in Appendix B show other aspects of pond operation. They examine the change in pond temperature profiles with season, extraction rate, effective Nusselt number, and temperature. Figures 20 and 21 show the Carnot efficiency decreases with increasing extraction rate or Nusselt number, respectively. The last graph generated from the simulation, Figure 22, shows the Carnot efficiency as a function of the month of the year. The curve has a sinusoidal shape, the efficiency being best in fall and worst in spring. A higher Nusselt number will shift the peaks of the curve later in the year, and decreases the overall efficiency.

Equipment Tests

The test chamber insulation and heater efficiency test results are graphed in Appendix C (Figures 23 thru 32). Eleven heater efficiency trials were performed on the above heated bottle test apparatus, and the calculated efficiencies were found to be a function of plate temperature. Two trials were also run for the above heated dewar tests.

Figure 8. Temperature vs. Position (x/D)
Void Fraction Contours
Computer Simulation

Figure 9. Carnot Efficiency vs. Extraction Rate
Void Fraction Contours
Computer Simulation

Figure 10. Max. Sphere Dia. vs. Nusselt No.
Void Fraction Contours
Computer Simulation

One test run was used for the below heated and insulation tests. Efficiency and insulation calculations are also included in Appendix C, and are summarized in Table 2.

Above Heated Tests

The transient behavior of two heated from above bottle tests was studied (Fig. 11 and 14). It was found that after about 20 hours of heating, the temperature gradient remained constant.

A typical steady state temperature gradient is shown in Figure 12. These gradients were shown to be linear. Seven different bottle arrangements and three types of broken glass/water mediums were tested in the above heated orientation. These tests are presented in Appendix D (Fig. 33-64). In this position, only conduction is taking place. Using the corrected power settings and the temperature gradients from the graphs, the effective thermal conductivities were calculated. A summary of these tests and calculations is presented in Table 3.

The thermal conductivities determined from these tests are plotted against the void fraction in Figure 13. The data are compared to a theoretical curve that considers the thermal conductivity to be

$$\lambda_m = \epsilon \lambda_f + (1-\epsilon) \lambda_g. \quad (6)$$

Bottom Heated Tests

Seven types of bottle arrangements and three kinds of broken glass/water porous mediums were heated from below. The tests are summarized in Table 4, and the remaining results presented in Appendix E (Fig. 65-73). The larger the temperature gradient within the medium,

<u>Heated From</u>	<u>Container</u>	<u>Heater Efficiency</u>	<u>Conductance R ($^{\circ}\text{C/W}$)</u>
Above	Can	$=.3975-.011 T_p^*$	10.95
Below	Can	$=.92$	26.46
Above	Dewar	$=.072$	12.11
Below	Dewar	$=1.0$	12.11

* T_p = Heating Plate Temperature

Table 2. Equipment Efficiency Summary

Figure 11. Temperature vs. position
 Time Test $q = 25 \text{ W/in}^2$
 Rectangular/Random/ $\epsilon = .329$
 Heated From Above

Figure 12. Temperature vs. Position
Med. Cyl./Ordered/ $\epsilon=.85$
Heated From Above $q=14.6 \text{ W/m}^2$

Figure 13. Thermal Conductivity vs. Void Fraction Heated From Above Tests

Figure 14. Temperature vs. Position
 Med. Cyl/Random/ $\epsilon=.851$
 Heated From Below

Figure	Bottle	Packing	ϵ	$q(W/m^2)$	$\Delta T/\Delta X(^{\circ}C/cm)$	$\lambda_{calc}(W/mK)$	$\lambda_{ave}(W/mK)$
33	Large	Ordered	.871	14.7	1.52	.60	.607 $\pm$.007
34				20.0	2.06	.608	
35				33.4	3.38	.613	
36	Small	Ordered	.766	20.0	2.01	.627	.655 $\pm$.037
37				33.0	3.25	.640	
38				74.0	6.60	.697	
12	Medium	Ordered	.850	14.6	1.45	.625	.633 $\pm$.009
39				20.0	1.98	.632	
40				35.0	3.38	.643	
41	Rect	Ordered	.791	14.5	1.38	.652	.640 $\pm$.009
42				17.6	1.70	.642	
43				20.0	1.28	.637	
44				35.0	3.43	.630	
45	Medium	Random	.85	14.7	1.45	.632	.621 $\pm$.012
46				20.0	2.01	.623	
47				20.0	2.03	.608	
48	Irreg	Random	.832	25.0	2.16	.718	.718
49				48.4	3.33	.903	
50	Rect	Random	.829	25.0	2.34	.665	.664 $\pm$.043
51				48.0	4.45	.670	
52				16.0	1.65	.607	
53				16.0	1.40	.712	
54	Broken		.797	24.5	2.06	.740	.703 $\pm$.029
55				10.6	.94	.70	
56				6.8	.64	.668	
57				8.6	.76	.702	
58	Broken		.660	25.9	2.24	.720	.702 $\pm$.046
59				10.6	1.02	.648	
60				7.0	.64	.683	
61				8.6	.71	.755	
62	Broken		.513	23.8	1.85	.797	.80 $\pm$.016
63				36.8	2.92	.783	
64				61.8	4.67	.822	

Table 3. Above Heating Test Results

<u>Figure</u>	<u>Bottle</u>	<u>Packing</u>	<u>ϵ</u>	<u>$q(W/m^2)$</u>	<u>$\Delta T/\Delta X$ ($^{\circ}C/cm$)</u>
65	Large	Ordered	.866	322 80.96 39.56	-- -- --
14	Medium	Random	.851	80.96 156.4 257.6 460.	-- -- -- --
66	Irregular	Random	.832	304 883 1122 1122	-- -- -- --
67	Small	Random	.819	80.5 156.4 322	-- -- --
68	Rectangular	Random	.812	304 506 883 1122	-- -- -- --
69	Small	Ordered	.761	506 1122 304 34.0	-- -- -- --
70	Rectangular	Ordered	.759	138 304 506	-- -- --
71	Broken		.643	81.2 358.9 4208 2367	-- -- -- --
72	Broken		.585	118 359 4208 2367	-- -- -- --
15	Broken		.513	359 251	1.45 .79
73	All water		1.0	304 506 883 1200	-- -- -- --

Table 4. Bottom Heating Test Results

the more the fluid has been stagnated, and the heat transfer reduced. Figure 14 shows a typical result from these tests. In all but one case, see Fig. 15, the change in temperature across the medium was too small to be accurately estimated. The case of exception was for the most finely broken glass.

Calculations in Appendix F estimate the Nusselt number for this test at $Nu = 3.17$ to 4.13 . These conditions were placed in the numerical simulation. That simulation showed that heat transfer through the pond was too great and resulted in numerical instabilities.

Tank Tests

The tank was filled with medium cylindrical bottles to a depth of 25 cm and the temperatures observed over six sunny summer days. Table 5 shows that no temperature gradient was observed at anytime during that time. The pyranometer indicated that at best 25% of the incident sunlight reached the bottom of the tank.

An additional 16 cm of bottles were added to the pond, and the temperatures were monitored for another week (see Table 6). Again no temperature gradient was formed. The pyranometer readings showed that less than 10% of the incident sunlight passed through to the pond bottom.

Figure 15. Temperature vs. Position
Broken/ $\epsilon=.513$
Heated From Below

LARGE TANK DATA

Medium Cylindrical Bottles (Random Order)

Note: x = 0 at pond bottom

<u>Channel</u>	<u>Position</u>			<u>2pm</u> <u>Day 1</u>	<u>11:30am</u> <u>Day 2</u>	<u>3pm</u> <u>Day 2</u>	<u>6:20am</u> <u>Day 2</u>	<u>11:30am</u> <u>Day 3</u>	<u>1:45pm</u> <u>Day 4</u>	<u>3:30pm</u> <u>Day 5</u>	<u>1:40pm</u> <u>Day 6</u>
	<u>X (cm)</u>	<u>R (cm)</u>	<u>θ</u>	Start	Temperatures (°C)						
38	0	20.3	-45		25.6	27.6	27.3	25.4	26.6	26.4	26.1
37	1.3	10.2	0		25.5	27.9	27.4	25.4	27.0	26.7	26.3
40	7.6	12.7	90		25.6	27.9	27.5	25.7	26.9	26.9	26.4
42	8.9	12.7	0		25.7	27.9	27.4	25.5	26.9	26.9	26.3
39	25.4	12.7	30		25.7	27.8	27.3	25.9	26.8	26.9	26.7
41	25.4	17.8	-90		25.6	27.6	27.2	25.7	26.8	26.8	26.6

Table 5. Large Tank Data H=25 cm Filled with Med. Cyl. Bottles

LARGE TANK DATA:

Medium Cylindrical & Rectangular Bottles

Note: X=0 at pond bottom

<u>Channel</u>	<u>Position</u>			<u>Temperature ($^{\circ}\text{C}$)</u>		
	<u>X(cm)</u>	<u>R(cm)</u>	<u>θ</u>	<u>Noon Day 1</u>	<u>4:40pm Day 2</u>	<u>2:00pm Day 3</u>
				<u>3:00pm Day 4</u>		
			Start			
38	0	20.3	-45	27.0	26.0	26.4
37	1.3	10.2	0	27.1	25.7	26.6
40	7.6	12.7	90	28.2	26.3	27.0
42	8.9	12.7	0	27.7	25.3	26.7
39	25.4	12.7	30	29.7	25.7	27.9
41	40.6	17.8	-90	30.5	28.1	29.4

Table 6. Large Tank Filled with Rectangular
and Medium Cylindrical Bottles Data

DISCUSSION OF RESULTS

Comparisons to Membranes and Cells

The calculations in Appendix F have shown that if our test conditions are roughly approximated to stratified membranes or rectangular cells, convective heat transfer will be present. These predictions compare favorably to the observed data. The stratified membrane estimates an observable temperature gradient between a void fraction of .6 to .7, but one was not seen until the void fraction was equal to .5. This suggests that more paths of fluid motion were available in our broken glass mediums, and so more convection was present.

Numerical Analysis

The efficiency of a glass sphere solar pond is at least 50% lower than a salt gradient pond because the thermal conductivity is 50% higher for a half glass, half water mixture. The Carnot efficiency of the pond was shown to decrease rapidly with the onset of convection. For $Nu > 2$, the simulation became increasingly unstable.

The spheres needed to suppress convection were found to be less than 5 mm in diameter. One meter deep pond would need a depth of about 200 spheres. Considering that a .4 m deep pond was observed to receive less than 10% of the incoming radiation at pond bottom, and that was with at least one quarter of the number of glass-water interfaces, we might expect less than 4% of the incident sunlight transmitted to the bottom. A solar pond will not function under these conditions. Sunlight not absorbed will be either reflected or absorbed in higher layers

and warm the water there. This will prevent the pond from establishing a desired temperature gradient.

Equipment Tests

A low heater efficiency was noted in the above heated dewar tests probably because the heating tape was not completely submerged. This caused heat to be lost to the ambient environment. When this same heater was submerged in the below heated tests, it operated at almost 100% efficiency.

The insulation of the test containers was quite sufficient as evidenced by the high thermal resistance values in the equipment tests and by the linear temperature profiles of the above heated tests. If the insulation had been lacking in these tests, heat leaving the sides of the container could have been detected by a non linear profile.

Above Heated Tests

It is possible that convective currents were present as the medium heated up, but that was not observable in our tests. The thermal conductivities, found from the steady state tests, were calculated to within about 10% based on the standard deviations of repeated trials. These results are reasonably close to those predicted by Eq. 6.

Below Heated Tests

The heated from below tests did not show the fluid to be stagnated. This was simply due to an inadequate amount of glass surface in the medium for the water to form convection resisting viscous boundary layers.

The porous medium took on a uniform temperature, while sharp temperature gradients were observed at the heat source and sink. The large size of the bottles relative to the test chamber might have created wall effects. Less restrictive paths might have been formed along the sides of the chamber, allowing the water to flow more freely.

Running tests in a large tank, where wall effects are minimized, and seeing similar results, confirmed our belief that convective behavior was due to the medium and not to the container.

Tank Tests

Solar ponds require a relatively long time period to begin to operate, but after two weeks of observation, the small solar pond did not show the slightest amount of temperature increase at its bottom. The deeper pond shows solar radiation absorbed near the surface causes the pond to be warmer near the top. That in itself would strongly suggest that the glass bottle/water medium was not suppressing convection. In addition, the fact that less than 10% of the incoming radiation was transmitted through the medium is reason to believe that the addition of glass bottles to the tank of water did not make an effective nonconvective zone.

Error Estimate

Our data collection apparatus limited us to an accuracy of $\pm 1^{\circ}$ C. In addition, positions of the thermocouples in the porous medium were only accurate to ± 1 centimeter. This inaccuracy occurred because of bottle shifting after the measurements were taken and from difficulties in defining positions during set up.

There were further errors in the reduction of the data. The heater efficiencies were averaged but actually there was a 12% difference between some of these estimates. Finally there was an error in taking the slope of the temperature gradients that was in the order of 10%. These errors were not sufficient to add doubt to the observation that convection was not suppressed.

CONCLUSION

A recycled glass/water porous medium is unsuitable as the nonconvective zone in a solar pond. This conclusion is based on the evidence of four means of investigation.

First, roughly approximating the medium by stratified membranes and rectangular enclosures shows convection to be occurring.

Second, a numerical simulation of a solar pond of glass spheres estimates the required sphere diameter to suppress convection to be less than 5 mm. This size particle would create too many glass/water interfaces for a significant amount of radiation to reach the pond bottom. Even without this consideration, the heat loss through this medium would be at least 50% greater than through a layer of stagnated water.

Third, a test apparatus constructed to study the one dimensional heat flow through the porous medium when heated from below showed in 9 out of 10 cases that no recognizable temperature gradient had developed. The exception showed a Nusselt number of 3.7, a value too high for efficient pond performance.

Fourth, a small scale recycled glass bottle solar pond also failed to develop a temperature gradient. The outdoor tank also indicated that only a small fraction of sunlight had reached the pond bottom.

While recycled glass bottles and fragments will not be of use in a nonconvection zone, they may be used in the lower convective zone. A water filled bottle in that zone will displace more expensive salt, and still be able to hold heat well.

APPENDIX A

COMPUTER PROGRAM

SAMPLE OUTPUT

Program Sunfun

```

100 DIM A(200),G(200),P(200),C(200),K(200),Q(200),R(200),T(2,500)
200 FOR S7=1 TO 16
270 PRINT'SI UNITS ARE USED THROUGHOUTTHE PROGRAM.'
280 PRINT
290 PRINT'PROGRAM EXECUTION BEGINS NOW'
300 PRINT
310 PRINT
320 PRINT'INPUT THE POND DEPTH,VOID FRACTION,EXPECTED'
330 PRINT'NUSSOLT NUMBER,AND EXTRACTION RATE'
340 INPUT D1,V1,N9,Q7
342 PRINT D1,V1,N9,Q7
345 F1=50
350 J3=0
355 P3=.1
360 P7=1000.
365 C7=1.0
370 K7=0
373 N1=1
375 N=3
380 X1=D1/(N-1)
390 PRINT'THE NODAL SPACING IN METERS='X1
400 PRINT
410 T1=24.
420 PRINT'A TIME INCREMENT OF 24 HOURS HAS BEEN ASSUMED'
500 PRINT
510 D2=X1*N1
520 PRINT'GROUND WATER TEMP IS REACHED AT'D2;'METERS BELOW'
530 PRINT'THE POND BOTTOM'
540 J=N+N1
550 PRINT
560 PRINT
570 PRINT
580 FOR I=1 TO J
590 T(1,I)=283.
600 T(2,I)=283.
610 NEXT I
620 PRINT'ALL POND AND GROUND TEMPERATURES ARE INITIALLY SET AT 10 C'
630 PRINT
640 PRINT
650 PRINT'POND WATER DENSITY, SPECIFIC HEAT, AND THERMAL CONDUCTIVITY'
660 PRINT'ARE ASSUMED TO BE FUNCTIONS OF THE VOID FRACTION AND'
670 PRINT'THE TEMPERATURE.'
700 REM V1 IS THE FRACTION OF WATER AND
701 REM V2 IS THE GLASS FRACTION
702 V2=1.0-V1
730 PRINT
740 REM LIST THE DENSITY COEFFICIENTS

```

```

1350 GO TO 1365
1351 IF F8>11 THEN 1354
1352 D4=31
1353 GO TO 1365
1354 IF F8>12 THEN 1357
1355 D4=30
1356 GO TO 1365
1357 IF F8>13 THEN 1360
1358 D4=31
1359 GO TO 1365
1360 D4=365
1365 D8=0
1366 E2=0.0
1367 REM BEGIN FINITE DIFFERENCE CALCULATIONS FOR THE
1370 REM POND AND GROUND TEMPERATURES
1395 F2=D4*F1
1400 FOR D3=1 TO F2
1405 F3=D3/F1
1410 D6=D5+F3
1420 REM H2 INCLUDES EFFECTIVE SURFACE TRANSMITTANCE
1430 REM H2 UNITS ARE W-HR/M2
1440 H2=11.628*(362.-230.*COS((D6+16)*2.*3.1416/365.))
1445 H2=H2/F1
1450 FOR I=1 TO N
1460 X=(X1)*(I-1)
1470 P(I)=U1*(C2+C1*T(1,I))+U2*2595.
1480 C(I)=U1*(C4+C3*T(1,I))+U2*.2313
1490 K(I)=U1*(C6+C5*T(1,I))+U2*1.02
1491 D8=N/2
1492 IF I>D8 THEN 1495
1493 J7=K(I)/((C4+C3*T(1,I))*(C2+C1*T(1,I)))
1495 K(I)=K(I)*N9
1510 A(I)=K(I)/(P(I)*C(I))
1520 NEXT I
1530 A7=K7/(P7*C7)
1540 FOR I=1 TO N
1550 IF I=1 THEN 1580
1560 X=X1*(I-1)-D1/((N-1)*2)
1570 GO TO 1590
1580 X=0
1590 M1=N1*(EXP(-U1*X)-P3*EXP(-U1*(2*D1-X)))
1600 M2=N2*(EXP(-U2*X)-P3*EXP(-U2*(2*D1-X)))
1610 M3=N3*(EXP(-U3*X)-P3*EXP(-U3*(2*D1-X)))
1620 M4=N4*(EXP(-U4*X)-P3*EXP(-U4*(2*D1-X)))
1630 R(I)=H2*(M1+M2+M3+M4)
1640 NEXT I
1650 FOR I=1 TO N-1
1660 Q(I)=R(I)-R(I+1)
1670 NEXT I
1680 Q(N)=R(N)
1690 T3=284.-14.*COS(2*D6*3.1416/365)
1700 T4=283.
1710 T(2,1)=T3
1720 X2=X1**2

```

```
770 C1=-.365
800 C2=1103.0
810 REM LIST THE SPECIFIC HEAT COEFFICIENTS
840 C3=-0.0002
870 C4=1.2223
880 REM LIST THE THERMAL COND COEFFICIENTS
910 C5=.00135
940 C6=.2014
1010 PRINT
1020 REM SET UP RADIATION GRADIENT IN POND USING RABL AND
1030 REM NIELSEN'S MODEL
1040 N1=.237
1050 N2=.193
1060 N3=.167
1070 N4=.179
1080 U1=.032
1090 U2=0.45
1100 U3=3.0
1110 U4=35.0
1120 PRINT
1290 Q1=Q7*24
1295 Q1=Q1/F1
1300 REM Q1 IS IN W-HR/M2-DAY
1310 D5=0
1320 FOR F8=1 TO 14
1321 IF F8>1 THEN 1324
1322 D4=1095
1323 GO TO 1365
1324 IF F8>2 THEN 1327
1325 D4=31
1326 GO TO 1365
1327 IF F8>3 THEN 1330
1328 D4=28
1329 GO TO 1365
1330 IF F8>4 THEN 1333
1331 D4=31
1332 GO TO 1365
1333 IF F8>5 THEN 1336
1334 D4=30
1335 GO TO 1365
1336 IF F8>6 THEN 1339
1337 D4=31
1338 GO TO 1365
1339 IF F8>7 THEN 1342
1340 D4=30
1341 GO TO 1365
1342 IF F8>8 THEN 1345
1343 D4=31
1344 GO TO 1365
1345 IF F8>9 THEN 1348
1346 D4=31
1347 GO TO 1365
1348 IF F8>10 THEN 1351
1349 D4=30
```

```

1730 FOR I=2 TO N-1
1740 R1=(1-2*A(I)*T1/X2)*T(1,I)
1750 R2=(A(I)*T1/X2+T1*(K(I+1)-K(I-1))/(4*X2*P(I)*C(I)))*T(1,I+1)
1760 R3=(A(I)*T1/X2-T1*(K(I+1)-K(I-1))/(4*X2*P(I)*C(I)))*T(1,I-1)
1770 R4=Q(I)/(X1*P(I)*C(I))
1780 T(2,I)=R1+R2+R3+R4
1790 NEXT I
1800 REM CALCULATE TEMPERATURE AT POND BOTTOM
1810 S1=(P7+P(N-1))*(C7+C(N-1))
1820 S2=(K7+K(N-1))/S1
1830 R1=(1-4*T1*S2/X2)*T(1,N)
1840 R2=(2*S2*T1/X2+T1*(K7-K(N-1))/(X2*S1))*T(1,N+1)
1850 R3=(2*S2*T1/X2-T1*(K7-K(N-1))/(X2*S1))*T(1,N-1)
1860 IF J3=0 GO TO 1930
1870 E4=1-T(1,1)/T(1,N)
1880 IF E4<=.01 GO TO 1910
1890 Q1=Q6/E4
1900 GO TO 1930
1910 Q1=0
1920 D8=D8+1
1930 R4=(4*(Q(N)-Q1)/(X1*S1))
1940 T(2,N)=R1+R2+R3+R4
1950 REM CALCULATE GROUND TEMPERATURES
1960 FOR I=N+1 TO J-1
1970 R1=(A7*T1/X2)*(T(1,I+1)+T(1,I-1))
1980 R2=(1-2*T1*A7/X2)*T(I,I)
1990 T(2,I)=R1+R2
2000 NEXT I
2010 T(2,J)=T4
2020 REM SET NEW TIME VALUES EQUAL TO THE OLD TIME VALUES
2030 FOR I=1 TO J
2040 T(1,I)=T(2,I)
2050 NEXT I
2060 E1=1-T(1,1)/T(1,N)
2070 IF E1<0 THEN E1=0
2080 E2=E2+E1
2090 REM RETURN TO NEXT TIME INCREMENT
2100 NEXT D3
2110 PRINT'*****'
2120 PRINT
2130 PRINT
2140 E3=E2/D4
2150 PRINT'THE AVERAGE CARNOT EFFICIENCY ='E3
2158 IF F8=14 THEN 2164
2159 F9=F8-1
2160 PRINT'FOR MONTH NUMBER';F9
2161 IF F9=1 THEN 2220
2162 IF F9=7 THEN 2220
2163 GO TO 2540
2164 PRINT'OVER A YEAR'
2165 GO TO 2545
2220 PRINT
2230 PRINT
2240 PRINT

```

```

2250 PRINT'SURFACE TEMP ='T(2,1);' KELVIN'
2260 PRINT'DENSITY ='P(1);' KG/M3'
2270 PRINT
2272 T9=T(2,1)
2274 X9=0.0
2280 FOR I=2 TO N-1
2290 X=X1*(I-1)
2300 L=X/D1
2302 IF T(1,I)>T9 THEN 2306
2304 GO TO 2310
2306 T9=T(1,I)
2308 X9=X
2310 PRINT'AT POND DEPTH'X;' M , TEMP='T(1,I);' KELVIN'
2320 PRINT'DENSITY ='P(I);' KG/M3'
2330 PRINT'DIMENSIONLESS POND DIST X/D='L
2340 PRINT
2350 NEXT I
2360 PRINT'POND BOTTOM TEMP='T(1,N);' KELVIN'
2370 PRINT'DENSITY='P(N);'KG/M3'
2380 PRINT
2390 FOR I=N+1 TO J
2400 X=X1*(I-1)-X1*(N-1)
2410 PRINT'AT'X;' M BELOW THE POND BOTTOM,GROUND TEMP='T(1,I);' KELVIN
2420 NEXT I
2430 PRINT
2440 PRINT
2450 D5=D5+D4
2460 PRINT'*****'
2461 F7=((T(1,N)+T(2,1))/2.0-293.)/100.
2462 A1=2.606
2463 A2=1.335
2464 A3=-.4762
2465 V8=.000001/(1.+A1*F7+A2*F7**2+A3*F7**3)
2466 B1=(1.8+6.48*F7)/10000.
2467 P9=V8/J7
2468 A5=V1**3/(150.*(1.-V1)**2)
2470 PRINT
2480 PRINT
2490 FOR F6=1 TO 3
2492 IF N9>1 THEN 2508
2494 IF F6=2 THEN 2502
2496 IF F6=3 THEN 2536
2498 A6=38.
2499 PRINT J7,V8,B1,T9,T(2,1)
2500 GO TO 2504
2502 A6=39.478
2504 A9=((V8*J7*A6)/(B1*A5*9.8*(T(1,N)-T(2,1))*D1))**.5
2506 GO TO 2530
2508 IF F6=1 THEN 2536
2510 IF F6=3 THEN 2524
2512 IF N9>3 THEN 2518
2514 B2=(LOG(N9)+1.023)/1.154

```

```
2516 GO TO 2520
2518 B2=(LOG(N9)+1.214)/.835
2520 A9=((10.**B2*V8*J7)/((T(1,N)-T(2,1))*B1*A5*9.8*D1))**.5
2522 GO TO 2530
2524 IF N9<5 THEN 2536
2526 R9=((9.8*B1*(T(1,N)-T(2,1))*D1*A5)/(J7*V8))**.5
2528 A9=LOG(N9/(.1*D1**.655*P9**.132*R9))/.345
2530 PRINT'METHOD =' ;F6
2532 PRINT
2534 PRINT'ESTIMATED GLASS SPHERE DIA.=' ;A9
2536 NEXT F6
2540 NEXT F8
2545 NEXT S7
2550 END
/
```

82/08/05. 20.49.47.
 PROGRAM SUNFUN
 INPUT THE POND DEPTH, VOID FRACTION, EXPECTED
 NUSSELT NUMBER, AND EXTRACTION RATE
 ? 1.5. .4764, 3, 10
 1.5 .4764 3 10
 THE NODAL SPACING IN METERS= .375

A TIME INCREMENT OF 24 HOURS HAS BEEN ASSUMED

GROUND WATER TEMP IS REACHED AT .375 METERS BELOW
 THE POND BOTTOM

ALL POND AND GROUND TEMPERATURES ARE INITIALLY SET AT 10 C

POND WATER DENSITY, SPECIFIC HEAT, AND THERMAL CONDUCTIVITY
 ARE ASSUMED TO BE FUNCTIONS OF THE VOID FRACTION AND
 THE TEMPERATURE.

THE AVERAGE CARNOT EFFICIENCY = 7.09337E-2
 FOR MONTH NUMBER 0

THE AVERAGE CARNOT EFFICIENCY = .173976
 FOR MONTH NUMBER 1

SURFACE TEMP = 271.947 KELVIN
 DENSITY = 1836.93 KG/M3

AT POND DEPTH .375 M , TEMP= 274.042 KELVIN
 DENSITY = 1836.56 KG/M3
 DIMENSIONLESS POND DIST X/D= .25

AT POND DEPTH .75 M , TEMP= 275.945 KELVIN
 DENSITY = 1836.23 KG/M3
 DIMENSIONLESS POND DIST X/D= .5

AT POND DEPTH 1.125 M , TEMP= 277.772 KELVIN
 DENSITY = 1835.91 KG/M3
 DIMENSIONLESS POND DIST X/D= .75

POND BOTTOM TEMP= 279.563 KELVIN
 DENSITY= 1835.6 KG/M3

AT .375 M BELOW THE POND BOTTOM, GROUND TEMP= 283 KELVIN

METHOD = 2

ESTIMATED GLASS SPHERE DIA.= .140247

THE AVERAGE CARNOT EFFICIENCY = .14479
FOR MONTH NUMBER 2

THE AVERAGE CARNOT EFFICIENCY = .147517
FOR MONTH NUMBER 3

THE AVERAGE CARNOT EFFICIENCY = .149194
FOR MONTH NUMBER 4

THE AVERAGE CARNOT EFFICIENCY = .147965
FOR MONTH NUMBER 5

THE AVERAGE CARNOT EFFICIENCY = .149194
FOR MONTH NUMBER 6

THE AVERAGE CARNOT EFFICIENCY = .147965
FOR MONTH NUMBER 7

SURFACE TEMP = 277.245 KELVIN
DENSITY = 1836.01 KG/M3

AT POND DEPTH .375 M , TEMP= 278.899 KELVIN
DENSITY = 1835.72 KG/M3
DIMENSIONLESS POND DIST X/D= .25

AT POND DEPTH .75 M , TEMP= 280.275 KELVIN
DENSITY = 1835.48 KG/M3
DIMENSIONLESS POND DIST X/D= .5

AT POND DEPTH 1.125 M , TEMP= 281.549 KELVIN
DENSITY = 1835.26 KG/M3
DIMENSIONLESS POND DIST X/D= .75

POND BOTTOM TEMP= 282.777 KELVIN
DENSITY= 1835.04 KG/M3

AT .375 M BELOW THE POND BOTTOM, GROUND TEMP= 283 KELVIN

METHOD = 2

ESTIMATED GLASS SPHERE DIA.= .129596

THE AVERAGE CARNOT EFFICIENCY = 8.64433E-2
FOR MONTH NUMBER 8

THE AVERAGE CARNOT EFFICIENCY = 9.54215E-2
FOR MONTH NUMBER 9

THE AVERAGE CARNOT EFFICIENCY = 9.38763E-2
FOR MONTH NUMBER 10

THE AVERAGE CARNOT EFFICIENCY = 9.54215E-2
FOR MONTH NUMBER 11

THE AVERAGE CARNOT EFFICIENCY = 9.38763E-2
FOR MONTH NUMBER 12

APPENDIX B

SIMULATION RESULTS

Figure 16. Temperature vs. Position
Season Contours
Computer Simulation

Figure 17. Temperature vs. Position
Extraction Rate Contours
Computer Simulation

Figure 18. Temperature vs. Position
Nusselt No. Contours
Computer Simulation

Figure 19. Temperature vs. Position
Pond Depth Contours
Computer Simulation

Figure 20. Efficiency vs. Extraction Rate
Pond Depth Contours
Computer Simulation

Figure 21. Efficiency vs. Nusselt No.
Extraction Rate Contours
Computer Simulation

Figure 22. Efficiency vs. Month
Nusselt No. Contours
Computer Simulation

APPENDIX C

INSULATION AND EFFICIENCY CALCULATIONS

CALCULATIONS

Insulation Effectiveness

$$\frac{T - T_{\infty}}{T_0 - T_{\infty}} = \text{Exp} \left(-\frac{UA}{\rho c_p V} t \right)$$

where T = Temperature at time t ($^{\circ}\text{C}$)

T_{∞} = Ambient temperature ($^{\circ}\text{C}$)

T_0 = Initial temperature ($^{\circ}\text{C}$)

ρ = Water density (kg/m^3)

c_p = Water specific heat (Whr/kgK)

V = Water volume (m^3)

t = Time (hr)

R = Thermal resistance = $1/UA = (^{\circ}\text{C}/\text{W})$

Doer: $T_0 = 31.65$

$T_{\infty} = 23.5$

$t = 28$

$T = 28.63$

$\rho c_p V = 5.0 \text{ W}\cdot\text{hr}/\text{K}$

$R = 12.11$

Above heated can: $T_0 = 42.0$

$T_{\infty} = 25.0$

$T = 32.7$

$t = 20$

$\rho c_p V = 2.31$

$R = 10.95$

Below heated can: $T_0 = 30.48$

$T_{\infty} = 25.0$

$T = 28.52$

$t = 27$

$\rho c_p V = 2.31$

$R = 26.46$

Calculations

Heater Efficiencies

Above Heated

$$\eta = \frac{\lambda \Delta T}{q_{in} \Delta X}$$

$$\lambda = .6 \text{ (W/mK)}$$

$$q_{in} = i^2 R \text{ (W/m}^2\text{)}$$

$$\frac{\Delta T}{\Delta X} \text{ (}^\circ\text{C/m)}$$

q_{in}	T_p	$\frac{\Delta T}{\Delta X}$	q_{act}	η
Dewar				
95	-----	.686	6.9	.073
147	-----	1.07	10.6	.072
Can				
40	27.6	1.40	13.5	.337
40	28.0	1.52	14.7	.368
40	30.1	1.56	15.0	.378
56	30.3	2.03	19.6	.350
56	32.8	2.11	20.4	.364
56	29.1	2.11	20.4	.364
100	36.2	2.92	28.2	.282
100	36.3	2.62	25.3	.253
100	43.1	3.63	35.0	.351
170	47.7	4.55	43.9	.258

Below Heated

$$\eta = \frac{mC_p \Delta T}{i^2 R \Delta t}$$

$$\text{Dewar } \eta = (4.3 \text{ kg})(1.16 \text{ Whr/kgK})(.34 \text{ }^\circ\text{C/hr}) / (.247)^2 (24.8) = 1.0$$

$$\text{Can } \eta = (17)(1.16)(.117) / (2.51) = .92$$

Figure 23. Temperature vs. Time
Test Chamber Insulation Test

Figure 24. Temperature vs. Position
Above Heated Efficiency Test
Test Chamber

Figure 25. Temperature vs. Position
Above Heated Efficiency Test
Test Chamber

Figure 26. Temperature vs. Position
Above Heated Efficiency Test
Test Chamber

Figure 27. Temperature vs. Position
Above Heated Efficiency Test
Test Chamber

Figure 28. Temperature vs. Position
Above Heated Efficiency Test
Test Chamber

Figure 29. Temperature vs. Position
Above Heated Efficiency Test
Test Chamber

Figure 30. Efficiency vs. Plate Temperature Above Heated Test Chamber

Figure 31. Temperature vs. Position
Dewar Above Heated Efficiency
 $q=95 \text{ W/m}^2$

Figure 32. Temperature vs. Position
Dewar Above Heated Efficiency
 $q=147 \text{ W/m}^2$

APPENDIX D

ABOVE HEATED GRAPHS

Figure 33. Temperature vs. Position
Large Cyl/Ordered/ $\epsilon=.871$
Above Heated $q=14.7 \text{ W/m}^2$

Figure 34. Temperature vs. Position
Large Cyl/Ordered/ $\epsilon=.871$
Above Heated $q=20.0 \text{ W/m}^2$

Figure 35. Temperature vs. Position
Large Cyl/Ordered/ $\epsilon=.871$
Above Heated $q=33.4 \text{ W/m}^2$

Figure 36. Temperature vs. Position
Small Cyl/Ordered/ $\epsilon=.766$
Above Heated $q=20.0 \text{ W/m}^2$

Figure 37. Temperature vs. Position
Small Cyl/Ordered/ $\epsilon=.766$
Above Heated $q=33.0 \text{ W/m}^2$

Figure 38. Temperature vs. Position
Small Cyl/Ordered/ $\epsilon=.766$
Above Heated $q=74. \text{ W/m}^2$

Figure 39. Temperature vs. Position
Medium Cyl/Ordered/ $\epsilon=.85$
Above Heated $q=20.0 \text{ W/m}^2$

Figure 40. Temperature vs. Position
Medium Cyl/Ordered/ $\epsilon=.85$
Above Heated $q=35.0 \text{ W/m}^2$

Figure 41. Temperature vs. Position
Rect/Ordered/ $\epsilon=.791$
Above Heated $q=14.5 \text{ W/m}^2$

Figure 42. Temperature vs. Position
Rect/Ordered/ $\epsilon=.791$
Above Heated $q=17.6 \text{ W/m}^2$

Figure 43. Temperature vs. Position
Rect/Ordered/ $\epsilon=.791$
Above Heated $q=20.0 \text{ W/m}^2$

Figure 44. Temperature vs. Position
Rect/Ordered/ $\epsilon=0.791$
Above Heated $q=35.0 \text{ W/m}^2$

Figure 45. Temperature vs. Position
Medium Cyl/Random/ $\epsilon=.85$
Above Heated $q=14.7 \text{ W/m}^2$

Figure 46. Temperature vs. Position
Medium Cy1/Random/ $\epsilon=.85$
Above Heated $q=20.0 \text{ W/m}^2$

Figure 47. Temperature vs. Position
Medium Cyl/Random/ $\epsilon=.85$
Above Heated $q=20.0 \text{ W/m}^2$

Figure 48. Temperature vs. Position
Irregular/Random/ $\epsilon=.832_2$
Above Heated $q=25.0 \text{ W/m}^2$

Figure 49. Temperature vs. Position
Irregular/Random/ $\epsilon=.832_2$
Above Heated $q=48.4 \text{ W/m}^2$

Figure 50.

Temperature vs. Position
Rectangular/Random/ $\epsilon=.829$
Above Heated $q=25.0 \text{ W/m}^2$

Figure 51. Temperature vs. Position
Rectangular/Random/ $\epsilon=.829$
Above Heated $q=48. \text{ W/m}^2$

Figure 52. Temperature vs. Position
Rectangular/Random/ $\epsilon=2.829$
Above Heated $q=16 \text{ W/m}^2$

Figure 53. Temperature vs. Position
Rectangular/Random/ $\epsilon=0.829$
Above Heated $q=16 \text{ W/m}^2$

Figure 54. Temperature vs. Position
Broken/ $\epsilon = .797$
Above Heated $q = 24.5 \text{ W/m}^2$

Figure 55. Temperature vs. Position
Broken $\epsilon = .797$
Above Heated $q = 10.6 \text{ W/m}^2$

Figure 56. Temperature vs. Position
Broken $\epsilon = .797$
Above Heated $q = 6.8 \text{ W/m}^2$

Figure 57. Temperature vs. Position
Broken/ $\epsilon = .797$
Above Heated $q = 8.6 \text{ W/m}^2$

Figure 50. Temperature vs. Position
Broken/ $\epsilon=.660$
Above Heated $q=25.9 \text{ W/m}^2$

Figure 59. Temperature vs. Position
Broken/ $\epsilon = .660$
Above Heated $q = 10.6 \text{ W/m}^2$

Figure 60. Temperature vs. Position
Broken/ $\epsilon = .660$
Above Heated $q = 7.0 \text{ W/m}^2$

Figure 61. Temperature vs. Position
Broken/ $\epsilon = .660$
Above Heated $q = 8.6 \text{ W/m}^2$

Figure 62. Temperature vs. Position
Broken/ $\epsilon = .513$
Above Heated $q = 23.8 \text{ W/m}^2$

Figure 63. Temperature vs. Position
Broken/ $\epsilon = .513$
Above Heated $q = 36.8 \text{ W/m}^2$

Figure 64. Temperature vs. Position
Broken/ $\epsilon = .513$
Above Heated $q = 61.8 \text{ W/m}^2$

APPENDIX E

HEATED FROM BELOW GRAPHS

Figure 65. Temperature vs. Position
Large Cyl/Ordered/ $\epsilon=.866$
Bottom Heated

Figure 66. Temperature vs. Position
Irregular/Random/ $\epsilon=.832$
Bottom Heated

Figure 67. Temperature vs. Position
Small/Random/ $\epsilon = .819$
Bottom Heated

Figure 68. Temperature vs. Position
Rectangular/Random/ $\epsilon=.812$
Bottom Heated

Figure 69. Temperature vs. Position
Small/Ordered/ $\epsilon=.761$
Bottom Heated

Figure 70. Temperature vs. Position
Rectangular/Ordered/ $\epsilon = .759$
Bottom Heated

Figure 71. Temperature vs. Position
Broken/ $\epsilon = .643$
Bottom Heated

Figure 72. Temperature vs. Position
Broken/ $\epsilon = .505$
Bottom Heated

Figure 73. Temperature vs. Position
All Water
Bottom Heated

Figure 74. Temperature vs. Position
 Irregular/Random/ $\epsilon=.832$
 Above Heated $q=25.0$ W/m²
 Time Test

APPENDIX F

THEORETICAL CALCULATIONS

Calculations

Nusselt Number for Observed Stagnation

q = Heat Flux W/m^2

λ = Thermal Conductivity $W/m-^{\circ}K$

$\Delta T/H$ = Temperature Gradient $^{\circ}C/m$

$$Nu = qH/\lambda\Delta T$$

Trial 1

$q=359$

$\lambda=.80$

$\Delta T/H=.0145$

$Nu=3.17$

Trial 2

$q=251$

$\lambda=.80$

$\Delta T/H=.0079$

$Nu=4.13$

Calculations

Approximate Heat Transfer Behavior

1. "Membrane Stratified Solar Ponds" [7] by J. R. Hull

- Use void fraction and glass thickness to find an equivalent distance between stratified membranes.

Assuming the glass is evenly packed,

$$\epsilon = \frac{d_{\perp}}{d_{\perp} + d_g}$$

where ϵ = void fraction

d_g = glass thickness = .31 cm

$d_{\perp}$ = distance between horizontal parallel plates cm

From Figure 5 in the paper we find an estimated temperature gradient for a given mean temperature (40 °C) and separation distance that just suppresses convection.

ϵ	$d_{\perp}(\text{cm})$	$\Delta T/\Delta X$ (°C/cm)	$d_{11}(\text{cm})$	$(\Delta T)(\Delta X)_{11}$	$d_o(\text{cm})$	$(\Delta T/\Delta X)_o$
.5	.31	----	.42	1.0	.34	----
.6	.465	1.0	.63	.25	.52	.50
.7	.723	.15	.98	.05	.80	.1
.8	1.24	.02	1.68	.01	1.38	.01
.9	2.79	.01	3.77	.01	3.10	.01

Here d_{11} is an equivalent vertical spacing ($d_{11} = .74d_{\perp}$) and d_o is a vertical tube arrangement ($d_o = .9d_{\perp}$).

2. "Critical Rayleigh Numbers for Natural Convection of Water Confined in Square Cells with L/D from 0.5 to 8" [12] by W. L. Heitz and J. W. Westwater

- Use a bottle height to approximate length of a square area (~ dia.) ratio. We use $L/D = 2.5$.

By their definition of Rayleigh number,

$$Ra = \frac{\rho^2 g \beta \Delta T \Delta X^3}{\mu \lambda}$$

We take our bottle height to be $\sim .1$ m, and assuming a 50°K difference across a one meter deep pond, $\Delta T = 5.0^\circ\text{K}$.

Calculating our expected Rayleigh number

$$Ra = \frac{(1000 \text{ kg/M}^3)^2 (9.8 \text{ m/s}^2) (.51 \frac{\text{Whr}}{\text{kgK}}) (.18 \times 10^{-3} \text{ K}^{-1}) (5.0 \text{ K}) (.1 \text{ m})^3 (3600 \text{ s/hr})}{(1.006 \times 10^{-3} \text{ kg/ms}) (.7 \text{ W/mK})}$$

$$= 2.3 \times 10^7$$

• From Fig. 12 in the paper, for our Rayleigh number and L/D , we see we are well within the realm of natural convection. This paper predicts that we will see natural convection in our bottle tests.

3. "Convection in a Closed Rectangular Region: The Onset of Motion"

[13] by Ivan Catton

- Define aspect ratios H_1, H_2 = bottle bottom length to bottle height
- Determine the critical Rayleigh number for this ratio
- Check to see if the flow is stagnated by Fig. 2 in the paper

$$H_1 = H_2 = .4$$

$$Ra_c = \frac{\beta g \Delta T L^4}{\nu \alpha} = \frac{(.18 \times 10^{-3}) (9.8) (5.0) (.1)^4}{(.658 \times 10^{-6}) (1.512 \times 10^{-7})}$$

$$Ra_c = 8.87 \times 10^6$$

The graph shows that for this condition, convection is not suppressed.

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