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CHAPTER 1

The Artis Problem

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ABSTRACT. The Artis aquarium has had difficulty maintaining a reasonable temperature in the recently install mammoth sea water tanks during the peak of summer. At this time the approximately 400 000 liters of water may be as much as 3 degrees Celsius too hot. This represents a considerable amount of energy to dissipate. Any solution to this problem must take into account the limited budget of the zoo, the heritage status of the building and the health of the fish in the tank. In this report, we analyse the major sources of energy entering and leaving the system. From this analysis, we find that the most effective method of reducing the water temperature is to increase the amount of evaporation from the system.

KEYWORDS: energy balance, water temperature, conductive and radiative energy

1. Introduction

The Artis zoo has a number of aquaria in one heritage building, each with its particular environmental requirements. A recent addition of a large mammoth tropical sea water tank has introduced some problems. This tank is situated in a corridor and measures 5 by 2.5 by 20 meters. The ideal temperature for the tropical fish in the mammoth tank is 24 degrees Celsius. As there is not much daylight, a dozen lamps have been placed just above the aquarium to make sure the fish inside are visible. However, these big lamps produce a lot of heat. When in summer time the outside temperature reaches 25 degrees, the temperature in the corridor containing the mammoth tanks increases up to 30 degrees. The water itself becomes 27 degrees, which is too hot for the fish inside. In the neighbourhood of the lamps, the temperature rises to 40 degrees. Just under the roof sometimes temperatures of 60 degrees have been measured. This information is summarized in figure 2(a).

The problem presented to us is to reduce the temperature of the water in the mammoth tank at a minimal cost with the constraints of minimal modification to the heritage building.

Throughout this report, we speak about observations and assumptions. The observations were done during two visits to the aquaria, where we could,

FIGURE 1. Observation of the aquarium roof.

among other things, inspect the basins in the catacombs and condensation above them, the (lack of) ventilation, and the construction of the whole building including basins, tanks and even the roof. See figure 1. Throughout the report, we also use various material constants. These are all taken from [1].

2. Facts about the Problem

We will restrict our analysis to the largest tank, the mammoth tank. The water in this system, approximately 440 000 l, is divided in two volumes. The first volume is the tank in the public area. The second is the reservoir in the catacombs where the water is oxygenated. The water is pumped through the system with a circulation time of approximately 4 hours. The water of the total system can get up to 3 degrees Celsius too hot. Although the water in the system appears to be well mixed, there is a difference in temperature between the reservoir and the tank of about 0.1 degrees Celsius. Since the tank contains sea water, it is not possible to use a simple heat exchanger to cool the tank as any metals introduced into the water will release ions which is bad for the fish.

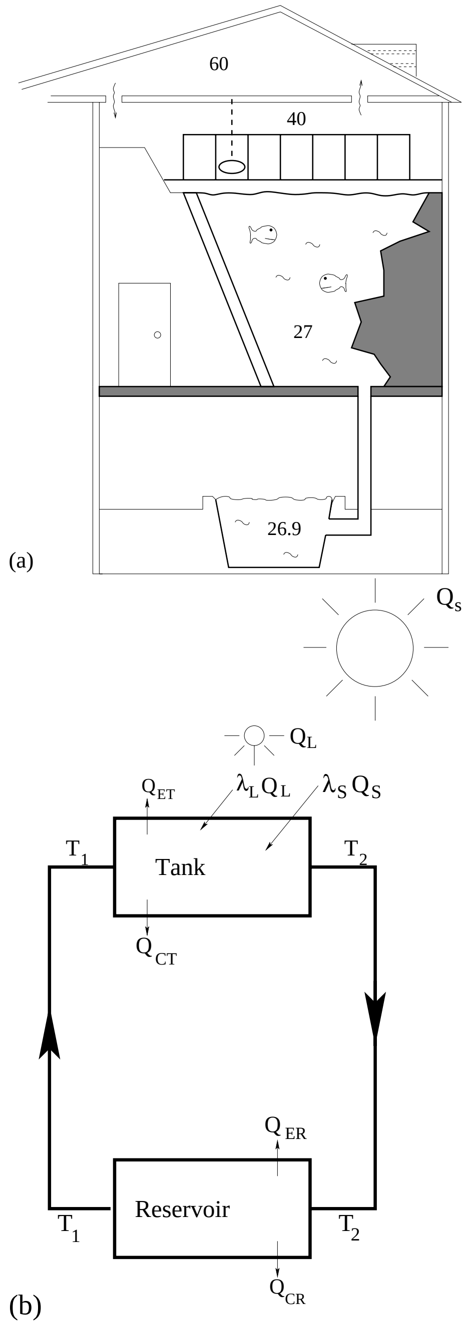

FIGURE 2. (a) Schematic picture of the mammoth tank and reservoir, (b) The energy inputs and outputs of the tank and reservoir.

3. Energy Balance

Here we consider the various energy sources and sinks in the system. To perform the energy balance, we will consider the mammoth system as two separate systems, i.e. the water in the tank and the water stored in the reservoir in the catacombs. In the tank the two main sources of energy are sunlight and the lamps heating the water. This energy is then either dissipated or stored in the water. The dissipation is conductive through the tank glass and walls. The water in the reservoir then dissipates more energy by evaporation and further conduction into the ground. We list each of these terms here.

Sources and Sinks	
Q_S	Solar Energy
Q_L	Energy from Lights
Q_{ET}	Evaporative Energy Loss from Tank
Q_{CT}	Conductive Energy Loss from Tank
Q_{ER}	Evaporative Energy Loss from Reservoir
Q_{CR}	Conductive Energy Loss from Reservoir
Constants and Variables	
λ_S	Percentage of Solar Energy Absorbed by Water
λ_L	Percentage of Light Energy Absorbed by Water
T_1	Temperature of Water in Tank
T_2	Temperature of Water in Reservoir
ΔT	Change in Temperature

Now we balance the energy in the tank and in the reservoir separately. First in the tank,

$$\lambda_S Q_S + \lambda_L Q_L = Q_{ET}(T_2) + Q_{CT}(T_2) + \theta \Delta T\,, \tag{1}$$

where θ is the amount of energy to change the temperature by 1 degree in the 4 hour cycle. The term $\theta \Delta T$ is the energy that is stored in the water as the temperature in the tank increases by ΔT. We calculate θ as

$$\theta = c\,\Phi\rho = \frac{4.18 \times 10^3 \cdot 4 \times 10^5}{4 \cdot 3600} \sim 10^5 \mathrm{WK}^{-1}. \tag{2}$$

Here c is the specific heat of water, Φ is the flow rate, and ρ the density. The energy balance in the reservoir is given by

$$\theta \Delta T = Q_{CR}(T_1) + Q_{ER}(T_1)\,. \tag{3}$$

Note that the decrement in the water temperature in the reservoir is equal to the increment in the tank. This decrement corresponds to the energy loss by conduction and evaporation. The situation is illustrated in figure 2(b). We may make some simplifications from the observations made at the aquarium. The air in the space above the tank appeared to be trapped and at 100 percent humidity, thus the evaporative energy losses in the tank system are negligible. The temperature change between the two systems, $\Delta T = T_1 - T_2$, is approximately 0.1 degrees Celsius, and thus we may take $T_1 \sim T_2 \sim T$. Under these assumptions, (1) and (3) may be simplified to

$$\lambda_S Q_S + \lambda_L Q_L = Q_{CT}(T) + Q_{CR}(T) + Q_{ER}(T)\,. \tag{4}$$

4. Detailed Analysis

In this section we will examine each term in (4) and find estimates of each one.

4.1. Energy Inputs. As very little convection was observed, we will assume that most of the energy enters the system by radiation. The total energy used by the lamps is approximately 10 kW. Since the lights are incandescent and very inefficient we will assume that all of this energy is transfered to the water. To find the energy added to the water from solar radiation, we use Stefan-Boltzmann law for black body radiation. In bad cases the temperature above the roof can reach 50 degrees Celsius or more and the water may be 25 - 27 degrees Celsius. We are finding the energy flux through a plane and thus divide the total energy by 2 as half will be transmitted and half will be reflected up. Finally, we estimate $\lambda_S \sim 1/2$. Thus, we have the following estimates for the energy inputs:

Lights

$$Q_L \sim 10\text{kW total}\,, \tag{5}$$

$$\lambda_L \sim 1\,, \text{estimate.} \tag{6}$$

Sun

$$Q_S \sim \frac{\sigma}{2}(T_{\text{roof}}^4 - T^4)A \sim 10\text{kW}\,, \tag{7}$$

$$\lambda_S \sim 0.5\,, \text{ estimate.} \tag{8}$$

Here $\sigma = 5.6 \times 10^{-8}$ Wm^{-2}K^{-4} is the Stefan-Bolztmann constant, T_{roof} is the temperature just under the roof, for which we took $T = 323$ K in this estimate, and $A = 5 \times 20$ m^2 is the area of the top of the tank. Furthermore, we took $T = 298$ K. For really hot days, when $T_{\text{roof}} = 333$ K (60 degrees C) and $T = 300$ K (27 degrees C), Q_S reaches about 20 kW.

Note here, that the order of magnitude of energy input by the lights and by the sun on warm days is the same. Even if we would have $\lambda_S \sim 1$, this is still the case.

4.2. Conductive Energy Losses. We will now estimate the energy loss in the system due to conduction. In the tank, we will assume that all of the energy is lost through the glass wall of the tank, as the back of the tank is made of thick rock and is a much better insulator. We will also assume that the energy is convected away from the glass ideally. Under these assumptions, we get

$$Q_{CT} = \mu_T (T - T_{\text{ambient}}) \,, \tag{9}$$

where μ_T is the total thermal conductivity of the glass wall in the tank and is given by

$$\mu_T = k \frac{A}{d} \,. \tag{10}$$

Here, A is the area of the glass, d is the thickness of the glass and k is the thermal conductivity of glass. When we substitute in these constants we find that $Q_{CT} = 0.93 \times 50/0.1 \sim 0.5$ kW.

The estimation of the energy loss in the reservoir is more complicated, as the heat will flow into the ground and we may not assume that the energy is being removed ideally at the outer surface of the reservoir. To simplify the calculations, we will assume that the reservoir is hemispherical in shape. Although this will overestimate the heat loss to the ground, the result will be of the same order of magnitude as the actual losses. To find the thermal conductivity of such a reservoir, we assume that the temperature profile in the soil outside of the reservoir is radially symmetric and given by

$$T_S(r) = \frac{T - T_{\text{soil}}}{r} R + T_{\text{soil}} \quad \text{for } r > R. \tag{11}$$

Here, T is the temperature of the water, T_{soil} is the temperature of the soil far from the reservoir, r is the distance from the centre of the reservoir and R is the radius of the reservoir. Since the approximate dimension of the reservoir is 15 meters by 35 meters, we approximate R by 10 meters. Moreover, we approximate T_{soil} by 16 degrees Celsius. The conductive loss of the reservoir into the ground is then given by

$$\begin{aligned} Q_{CR} &= -k(2\pi R^2) \left. \frac{\partial T_S}{\partial r} \right|_{r=R} , \\ &= 2\pi R k (T - T_{\text{soil}}) \,. \end{aligned} \tag{12}$$

In other words, the thermal conductivity μ_R of the reservoir is $2\pi R k$. Substituting all values into (12), we find that on a hot summer day, so for $T = 27$ degrees Celsius, the conductive loss in the reservoir is approximately 0.5 kW.

4.3. Evaporative Energy Losses. We now calculate the amount of energy removed from the system due to evaporation. We first make a few assumptions based on observations of the aquarium. We will assume that all of the evaporation occurs in the reservoir, since we observed much condensation near the air outlet in the catacombs, and no condensation above the tank. Moreover, the air just above the tank has the same temperature as the water inside the tank, and the area of the tank is much smaller than the area of the reservoir. We also assume that air enters the reservoir at 80%

saturation (typical conditions for Amsterdam in mid-summer) and then is fully saturated and leaves, via the vent, at 100% saturation. Under these assumptions, the evaporative loss is given by

$$Q_{ER} = \frac{\rho AVL}{p_{\text{atmos}}}(pp_{\text{inside}} - pp_{\text{outside}})\,, \tag{13}$$

where pp are the partial pressures of water vapour inside the catacombes and outside the building, ρ is the density of moist air (~ 1.3 kg/m^3), p_{atmos} is the atmospheric pressure (~ 100 kPa), L is the latent heat of water ($\sim 22.6 \times 10^5$ J/kg), A is the area of the vent ($\sim 0.04\text{m}^2$) and V is the velocity of air through the vent (and above the water). Since we have 100% saturation inside, we have $pp_{\text{inside}} = sp(T)$. Here sp is the saturation pressure at temperature T, and the air temperature is approximated by the water temperature. Outside, saturation is again expected to be 80% on average on a hot summer day, so $pp_{\text{outside}} = 0.8 \times sp(T_{\text{ambient}})$. In the summer, approximately 2 cubic meters of distilled water per week must be added to the system to maintain the volume. This is equivalent to approximately 6 kW of evaporation. Plugging this into (13), with $T = 27$ and an estimate of $T_{\text{amb}} = 20$ for the outside temperature averaged over a full hot day in summer, results in an air velocity of 2.4 m/s.

4.4. Summary of Energy Balance. Before proceeding to the full energy balance, we may compare one of our calculations with observed results. We will calculate the change of temperature in the reservoir and compare this to the observed change which is approximately 0.1 degrees Celsius. Recall, the temperature change in the reservoir is given by

$$\theta \Delta T = Q_{CR} + Q_{ER}\,, \tag{14}$$

where $\theta \sim 10^5 \text{WK}^{-1}$ is the amount of energy to change the temperature by 1 degree in the 4 hour cycle, Q_{ER} is the evaporative loss which is observed to be about 6 kW, and Q_{CR} is the convective loss which was calculated to be about 0.5 kW. Substituting this results in a value of $\Delta T = 0.065$ degrees Celsius, which is the right order of magnitude. We may now approximate $T_1 \sim T_2 \sim T$ indeed with some confidence. Substituting (13), (5), (7), (9) and (12) into (4) results in the following equation relating the temperature of the water with the ambient temperature, the heating effect of the sun (via the roof's temperature) and the velocity of air through the vent in the reservoir,

(15)

$$\begin{aligned}\tfrac{\sigma}{4}(T_{\text{roof}}^4 - T^4)A + 10 = \mu_T(T - T_{\text{amb}}) + \tfrac{\rho AVL}{p_{\text{atmos}}}(sp(T) - 0.8sp(T_{\text{amb}})) \\ +\mu_R(T - T_{\text{soil}})\,.\end{aligned}$$

We now approximate $sp(T)$ following estimates in [2], fitted to the values $T = 293$ and $T = 303$. This yields

$$sp(T) = 0.16 \times 10^12 \cdot \exp(-5.3 \times 10^3/T).$$

Roughly, this gives pressure values of 3 - 4 kPa in the range of interest. Using this estimate we provide graphs of relation (15) in figures 3, 4, 5 and 6.

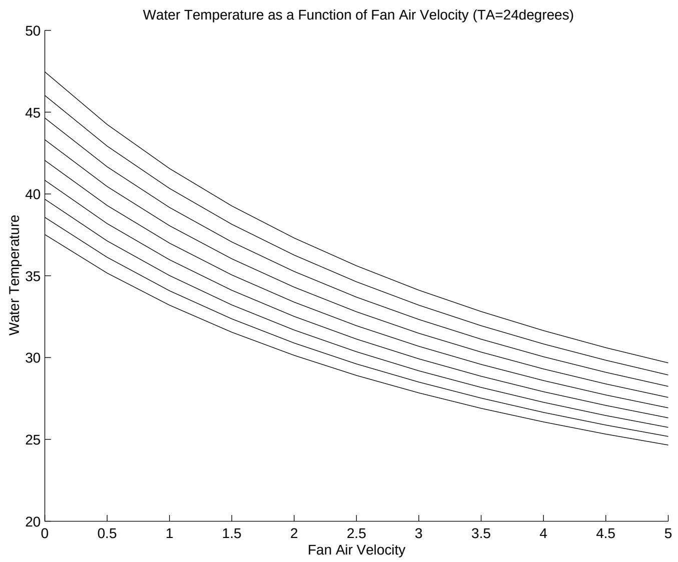

FIGURE 3. Water temperature versus fan air velocity. Higher lines correspond to higher roof temperature by the sun.

5. Conclusions

The above figures may be used as an indication of the relative influences on the water temperature of fan air velocity, ambient temperature and 'solar temperature', i.e. temperature just under the roof caused by the sun. Figures 4 and 5 show the dependence of the water temperature on the ambient and solar temperatures for fixed fan air velocities. The lines in these figures have slopes between 0.1 and 0.4, so the dependence is not very strong. In figure 3 however, the lines have slope ~ -2 in the regime around the current fan air velocity. For fixed solar and ambient temperature, the water temperature decreases by about 3 degrees if the fan air velocity is doubled from 2.4 to 4.8 m/s.

Therefore we conclude from the figures that the largest gains may be obtained by increasing the flow of air through the reservoir. This is relatively inexpensive and should not interfere with the appearance of the building. However, it must be noted that in the construction of relation (15), it was

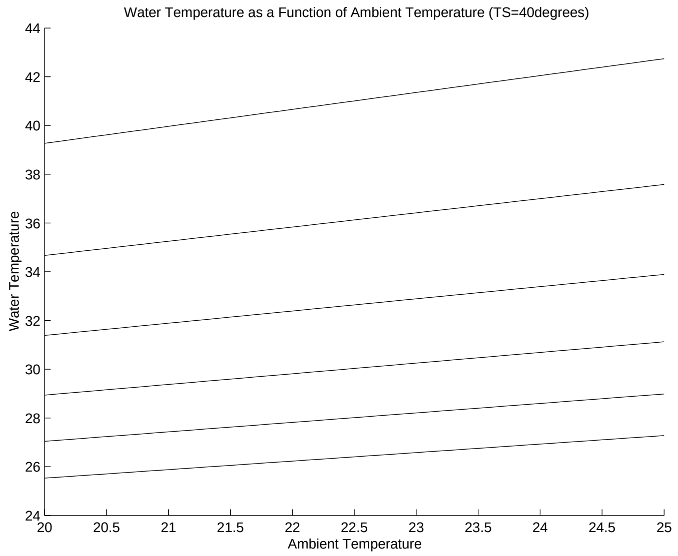

FIGURE 4. Water temperature versus ambient temperature. Lower lines correspond to increasing fan air velocity.

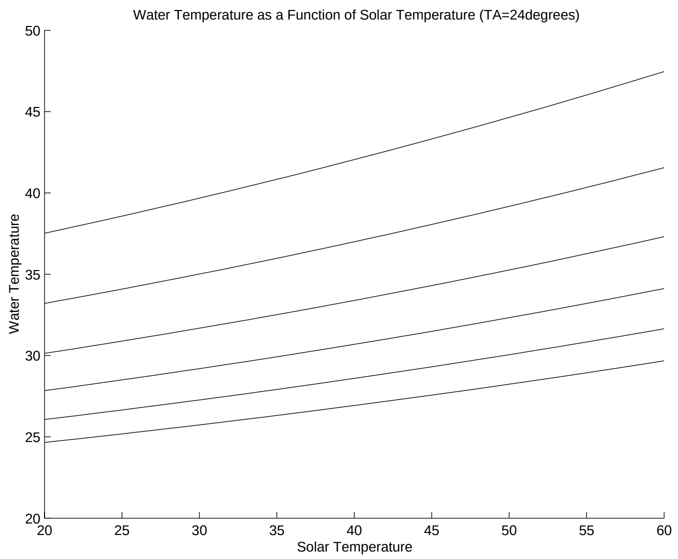

FIGURE 5. Water temperature versus solar temperature. Lower lines correspond to increasing fan air velocity.

assumed that an increase in the fan velocity will be proportional to the increase in water vapour leaving the system. This will not be true unless some care is taken. The area around the fan is very leaky and unless this

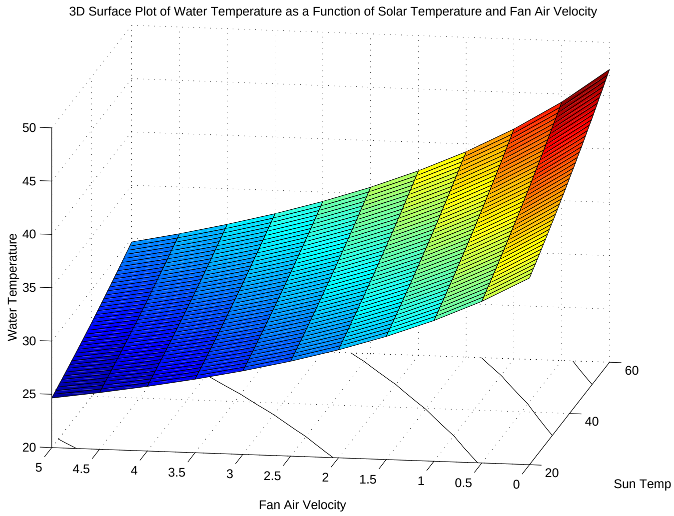

FIGURE 6. Overall picture.

is addressed, increasing the fan velocity will only draw outside air from the source near the fan. This will do nothing to increase evaporation. We also note that even though figure 5 suggest that reducing the amount of solar radiation will have a minimal effect on the temperature of the water, a reduction in the influx of solar energy could be achieved quite cheaply by reflective blinds or the growth of ivy and should thus also be considered.

Bibliography

[1] *Binas*, Wolters Noordhoff, Groningen, 1986.

[2] Education and outreach provided by the Planetary Atmospheres Node, *Encyclopedia of Standard Planetary Information, Formulas, and Constants*, `http://atmos.nmsu.edu/education_and_outreach/encyclopedia/sat_vapor_pressure.htm`