CHAPTER 15
AQUACULTURE

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15.1 INTRODUCTION

One of the most common areas of interest in geothermal direct use is that of aquaculture. For those involved with the initial planning of such a project, one of the first questions to be addressed relates to project size. In most geothermal applications, the maximum pond area that can be developed is restricted by the maximum heat available from the resource. It is the purpose of this chapter to present a brief introduction to the subject of heat loss from ponds (or pools) so that developers can make an informed evaluation of geothermal resources for this purpose.

15.2 TEMPERATURE REQUIREMENTS FOR SELECTED SPECIES

In order to determine the heat loss of the ponds, it is necessary to first select the temperature at which the water must be maintained. Table 15.1 provides a summary of appropriate temperatures for selected species. In addition, growth periods for cultures at optimum temperatures are shown in the last column.

15.3 HEAT EXCHANGE PROCESSES

A non-covered body of water, exposed to the elements, exchanges heat with the atmosphere by way of four mechanisms: (a) evaporation, (b) convection, (c) radiation, and (d) conduction. Each of these is influenced by different parameters that are discussed separately in the following paragraphs.

15.3.1 Evaporative Loss

Evaporation is generally the largest component of the total heat loss from the pond. Considering evaporation, the loss of volume generally comes to mind rather than the loss of heat. However, in order to boil water (and hence cause evaporation) heat must be added. The quantity of heat required to evaporate one pound of water varies with temperature and pressure, but under normal atmospheric conditions the value is approximately 1,000 British thermal units (Btu). When water is evaporated from the surface of the pond, the heat is taken from the remaining water. As a result, as each pound of water evaporates from the surface, approximately 1,000 Btu are lost with escaping vapor.

Table 15.1 Temperature Requirements and Growth Periods for Selected Aquaculture Species[a]

Species	Tolerable Extremes (ºF)	Optimum Growth (ºF)	Growth Period to Market Size (mos)
Oysters	32 to 97 typ	76 to 78 typ	24
Lobsters	32 to 88	72 to 75	24
Penaeid Shrimp			
Kuruma	40 to ?	77 to 87	6 to 8 typ
Pink	52 to 104	75 to 85	6 to 8
Salmon (Pacific)	40 to 77	59	6 to 12
Freshwater Prawns	75 to 90	83 to 87	6 to 12
Catfish	35 to 95	82 to 87	6
Eels	32 to 97	73 to 86	12 to 24
Tilapia	47 to 106	72 to 86	--
Carp	40 to 100	68 to 90	--
Trout	32 to 89	63	6 to 8
Yellow Perch	32 to 86	72 to 82	10
Striped Bass	? to 86	61 to 66	6 to 8

a. Behrends, 1978

Losses can occur by evaporation even when the water temperature is at or below the surrounding air temperature.

The rate at which evaporation occurs is a function of air velocity and the pressure difference between the pond water and the water vapor in the air (vapor pressure difference). As the temperature of the pond water is increased or the relative humidity of the air is decreased, evaporation rate increases. The equation that describes the rate of evaporation is (ASHRAE, 1995).

$$Wp = (0.097 + 0.038v) \cdot (Pw - Pa) \cdot A$$

where

Wp = rate of evaporation (lbm/h)
A = pond surface area (ft^2)
v = air velocity, (mph)
Pw = saturation vapor pressure of the pond water (psia)
Pa = saturation pressure at the air dew point (psia)

For enclosed ponds or indoor swimming pools, this equation can be reduced to (ASHRAE, 1995).

$$Wp = 0.204 \cdot A \cdot (Pw - Pa)$$

where

Wp = rate of evaporation (lbm/h)
A = pond area (ft^2)
Pw = saturation pressure of the pond water (psia)
Pa = saturation pressure at air dew point (psia)

Following are some common values for Pw and Pa:

For Pw: @ 60°F water, Pw = 0.256 psia
@ 70°F water, Pw = 0.363 psia
@ 80°F water, Pw = 0.507 psia
@ 90°F water, Pw = 0.698 psia

For Pa: For outdoor locations with a design dry bulb air temperature below 30°F, Pa can be taken as 0.074 psia.

For indoor locations with a design of approximately 75°F and 50% relative humidity, Pa can be taken as 0.211 psia.

For example, assume a pond with a surface area of 500 ft^2 (10 ft x 50 ft) located outside in an area with design temperature of 15°F. Wind velocity is 5 mph and pond water is to be 80°F.

$$Wp = (0.097 + (0.038 \cdot 5)) \cdot (.507 - .074) \cdot 500$$
$$= 62.1 \text{ lb/hr}$$

To obtain the heat loss (q_{EV}) in Btu/h, simply multiply the lbm/h loss by the value of 1,050 Btu/lbm.

$$q_{EV} = 62.1 \text{ lb/h} \cdot 1{,}050 \text{ Btu/lb}$$
$$q_{EV} = 65{,}200 \text{ Btu/h}$$

This is the peak or design heat loss. It is important to note that the example values given above are for the design (worst) case. At higher outdoor air temperatures and different relative humidities, this value would be less. As mentioned earlier, the rate of evaporation loss is influenced by the vapor pressure difference between the pond water and the water vapor in the air. Reduced water temperature would reduce the vapor pressure differences and hence, the rate of evaporation.

Wind speed over the surface of the water has a very substantial impact upon both evaporative and convective heat losses from ponds. When calculating the design heat loss for ponds, it is not necessary to use unrealistically high wind speeds. In general, the coldest outdoor temperatures are not accompanied by high wind speed conditions.

In addition, sustained high wind conditions are generally not experienced for extended periods of time. This, coupled with the high thermal mass of the water, allows the pond or pool to sustain brief high wind periods without significant water temperature drop.

Mean wind speeds which appear in Chapter 1 of the Department of Defense publication *Engineering Weather Data* (AFM 88-29)(1978) are appropriate values for these calculations.

Pond surface area can be influenced by surface disturbances due to waves or the use of splash-type aeration devices. The calculation presented above are based upon a calm water surface. If surface disturbances exist, the pond surface area ("A" in the above equation) should be increased to reflect the departure from the calm water condition.

15.3.2 Convective Loss

The next major mechanism of loss from the pond surface is that of convection. This is the mode associated with the heat loss caused by cold air passing over the pond surface. The two most important influences on the magnitude of convective heat loss are wind velocity and temperature difference between the pond surface and the air. This is evidenced in (Wolf, 1983):

$$q_{CV} = (0.198v) \cdot A \cdot (Tw - Ta)$$

where

q_{CV} = convection heat loss (Btu/h)
v = air velocity (mph)
A = pond area (ft^2)
Tw = water temperature (°F)
Ta = air temperature (°F)

The shape of the pond and the direction of the prevailing wind influences the magnitude of the convective heat loss. The method used here is appropriate for pond dimensions of up to approximately 100 ft . For very large ponds, convective losses would be up to 25% less than the figure which result from this method.

For an indoor pool, this equation would be (Lauer, undated):

$$q_{CV} = 0.38\ (Tw - Ta)^{0.25} \cdot A \cdot (Tw - Ta)$$

Using the example from above (15ºF design temperature, 80ºF water and 5 mph wind), the following convective heat loss can be calculated:

$$q_{CV} = (0.198v \cdot 5\ ft/s) \cdot 500\ ft^2 \cdot (80^o - 15^o)$$

$$q_{CV} = 32{,}200\ Btu/h$$

16.3.3 Radiant Loss

Radiant heat loss, the third largest component of the total heat loss is dependent primarily on the temperature difference between the pond surface temperature and the surrounding air temperature. Under normal circumstances, radiant heat exchange is assumed to occur between solid bodies with little or no gain to the air in between the bodies. However, because of the evaporative losses near the pond surface, the air tends to contain a large quantity of water vapor. When this is the case, the pond surface radiates to the water vapor in the air, which is assumed to be at the temperature of the air itself. The equation describing this process is (Stoever, 1941):

$$q_{RD} = 0.174 \cdot 10^{-8} \cdot 0.93\ [(460 + Tw)^4 - (460 + Ta)^4] \cdot A$$

where

q_{RD} = radiant heat loss (Btu/h)
Tw = pond water temperature (ºF)
Ta = air temperature (ºF)
A = pond surface area (ft^2)

Again referring to the above example (15ºF design temperature, 80ºF pond temperature), the following radiant heat loss is calculated:

$$q_{RD} = 0.174 \cdot 10^{-8} \cdot 0.93\ [(460 + 80^oF)^4 - (460 + 15)^4] \cdot 500$$

$$q_{RD} = 27{,}600\ Btu/h$$

15.3.4 Conductive Loss

The final mode of heat loss is that of conduction. This is the loss associated with the walls of the pond. Of the four losses, conduction is by far the smallest and in many calculations is simply omitted. The following method (ASHRAE, 1985) is valid for a pond depth of 3 to 5 ft.

$$q_{cd} = \{[(L + W) \cdot 2] + (L \cdot W \cdot 0.02)\}[(Tw - (Ta + 15)]$$

where

q_{CD} = conductive heat loss (Btu/h)
L = length of pond (ft)
W = width of pond (ft)
Tw = design water temperature (ºF)
Ta = design outside air temperature (ºF)

This calculation assumes the use of lined pond construction. That is, there is no significant leakage of water from the walls or floor of the pond.

Using the previous example, the following conductive heat loss is calculated:

$$q_{CD} = \{[(10 + 50) \cdot 2] + (10 \cdot 50 \cdot 0.02)\}\ [80 - (15 + 15)]$$

$$q_{CD} = 6{,}500\ Btu/h$$

Table 15.2 summarizes the results of the calculations performed for the example 500 ft^2 pond.

Table 15.2 Summary of Example Heat Loss

Heat Loss Method	Loss (Btu/h)	Amount (%)
Evaporation	65,200	50
Convection	32,200	24
Radiation	27,600	21
Conduction	6,500	5
TOTAL	131,500	100

These losses are the peak or maximum heat loss. At any given time during the year, other than the design case, the heat loss would be less than this value. The annual heating requirement cannot be determined from simply multiplying the peak heating requirement by 8760 h/y. Because of the need for consideration of varying temperature, wind, humidity, and solar heat gain, methods for calculating the annual heating requirement are beyond the scope of this chapter.

15.4 SURFACE COVER

Heat losses from the pond surface are most heavily influenced by wind velocity and the temperature difference between the pond and the surrounding air. Any method that can be employed to reduce these values can substantially reduce heating requirements.

For outdoor pools, a floating cover is an excellent example. The use of a 0.5 in. floating foam cover (on the pool surface) would reduce the peak heat loss for the example pool to the values shown in Table 15.3.

Table 15.3 Summary of Example Heat Loss Using Pool Cover

Heat Loss Method	Loss (Btu/h)	Amount (%)
Evaporation	0	0
Convection	5,200	35
Radiation	3,200	22
Conduction	6,500	43
TOTAL	14,900	100

This peak load is only approximately 11% of the originally calculated heat loss. This is, in large measure, a result of the elimination of evaporation loss that is provided by a floating type cover. Unfortunately, a floating cover is generally not considered practical for commercial aquaculture applications.

15.5 POND ENCLOSURE

A pond enclosure is another (though much more expensive) option for reducing heat loss. The advantages provided by an enclosure depend to a large extent upon the construction techniques employed (covering material, degree of enclosure, presence, or absence of ventilation. The variety of construction methods and materials available are too numerous to cover here. The basic advantages of an enclosure are: (a) reduced air velocity, (b) reduced temperature difference between the pond and surrounding air, and (c) reduced vapor pressure difference between the pond water and air (increased relative humidity). These effects reduce the losses associated with evaporation, convection and radiation.

Assuming an enclosure is placed over our example pond, reducing air velocity to the 10 to 30 ft/min range, increasing humidity to 90% and air temperature to 48^{o}F (half way between outside air and pond water temperature), pond heat loss would be reduced to the values shown in Table 15.4.

Table 15.4 Summary of Example Heat Loss Using Pond Enclosure

Heat Loss Method	Loss (Btu/h)	Amount (%)
Evaporation	35,200	47
Convection	14,500	19
Radiation	18,200	25
Conduction	6,500	9
TOTAL	74,400	100

This value amounts to 57% of the original example.

It is often erroneously believed that the use of a pond enclosure will allow the air within to become saturated and thus, eliminate evaporative loss from the pond surface. This is not the case in most applications. For greenhouse-type enclosures (the most common), the inside surface tempera-ture of the roof and walls is well below the dew point of the air during the winter. This results in substantial condensa-tion occurring on these surfaces. As a result, moisture is continuously removed from the air allowing more to be absorbed (through evaporation) from the pond surface.

For conventional constructed buildings, ventilation air is normally supplied to reduce humidity in the space to a point which will protect the structure from moisture damage. Under these conditions of course, evaporation continues to occur and an additional heating load is imposed by the requirement to heat the ventilation air. This topic is covered in detail in Chapter 4 of the *1995 ASHRAE Handbook of Applications*.

15.6 THERMAL MASS

One final method for reducing peak heating requirements for pond or pool heating lies in the use of the large thermal mass supplied by the water itself. Water is an excellent heat storage medium. Assuming the example pond is 5 ft deep and 500 ft^2 in area, the total volume con-tained would be 2,500 ft^3. At 7.49 gal/ft^3, this results in 18,725 gal or 156,000 lbm of water at 8.33 lbm/gal. Be-cause 1 lb of water gives up one Btu for each degree it is cooled, this means that our example pond that contains 156,000 lbm of water could provide 156,000 Btu of offset heating requirements if it were allowed to cool 1^{o}F. This stored heating capacity can be used to reduce the peak heating requirement on the heating system. Using the originally calculated peak heating requirement of 131,500 Btu/h, an example of thermal storage use follows. Assume that the peak heating requirement occurs over an 8-hour period after which, because of air temperature increase and solar gain, the heating load is reduced. Further, assume that the heating system is designed to supply only 80% of the peak requirement. What will happen to the pond temperature?

First, calculate the total heat required for the 8-hr period.

8 h · 131,500 Btu/h = 1,052,000 Btu

Second, calculate the heat that the system can supply based on its 80% capacity.

8 h · (0.80 · 131,500 Btu/h) = 842,000 Btu

Then, calculate the difference to be supplied by allowing the pond water to cool.

1,052,000 Btu - 842,000 Btu = 210,400 Btu

Finally, calculate the drop in pond temperature caused by supplying the heat required.

210,400 Btu/(156,000 lbm · 1 Btu/lbm°F) = 1.35°F.

As a result, the pond will have cooled by 1.35°F. The heating system would then bring the pond back up to the temperature during the day when higher temperatures and solar gain would reduce heating requirements.

An alternate way of looking at this is in terms of the selection of the ambient temperature to be used in the calculation of the pond losses. Use of the mean-duty temperature in-stead of the minimum-duty temperature would allow the design to incorporate the effect of the pond thermal mass on the heat loss. Use of an air temperature higher than the mean-duty value could be employed in very clear climates where solar heat gain can be assumed to contribute to pond heating during the day.

The degree to which thermal storage can be incorpo-rated into the heating system design is a complex issue of environmental factors, pond characteristics, and the species being raised. Some species, such as prawns, are particu-larly sensitive to temperature fluctuations (Johnson, 1978).

15.7 FLOW REQUIREMENTS

The rate of flow required to meet the peak heating demand of a particular pond is a function of the temperature difference between the pond water and the resource temperature. The following equation can be used to determine the flow (Q) requirement and is written:

$$Q = q_{tot}/[500 \cdot (Tr - Tw)]$$

where

Q = resource flow requirement (gpm)
q_{tot} = total calculated pond heat loss
$= q_{EV} + q_{CV} + q_{RD} + q_{CD}$
Tw = pond temperature (°F)
Tr = resource temperature (°F)
500 = constant (Btu/h gpm °F)

Assuming that our example pond is to be heated with a resource temperature of 100°F:

Q = 105,120 Btu/h/[500 · (100°F - 80°F)]
Q = 10.5 gpm

Again, the point is made that this is the peak requirement. The required flow at any other time would be a value <10.5 gpm. This approach is valid for aquaculture projects and resource temperatures up to levels that would prove harmful if supplied directly to the pond. Above this temperature (which varies according to species), the heating water would have to be mixed with cooler water to reduce its temperature. Two methods are possible for mixing. If a sufficient supply of cold water is available, the hot water could be mixed with the cold water before introduction in the pond. A second approach, which would apply in the absence of cold water, would be to recirculate pond water for mixing purposes. The recirculation could be combined with an aeration scheme to increase its beneficial effect. In both cases, the quantity of cold or recirculated water could be determined by the following formula:

$$Q_c = \frac{Q_h (T_h - T_m)}{(T_m - T_c)}$$

where

Q_c = required cold flow rate (gpm)
Q_h = hot water flow rate (gpm)
T_h = temperature of hot water (°F)
T_c = temperature of cold water (°F)
T_m = temperature of desired mixed water (°F)

The above methods are presented to provide interested individuals with an introduction to the subject of heat losses from ponds. The equations provided are simplifications of very complex relationships and should be employed only for initial calculations. In addition, losses that can occur from various aeration schemes and other activities have not been addressed. It is strongly recommended that a competent engineer be enlisted for final design purposes.

REFERENCE

American Society of Heating, Refrigeration and Air Conditioning Engineers, 1995. "Handbook of Applications, ASHRAE, Atlanta, GA.

American Society of Heating, Refrigeration and Air Conditioning Engineers, 1985. "Handbook of Fundamentals", ASHRAE, Atlanta, GA, pp. 25.6.

Behrends, L. L., 1978. "Waste Heat Utilization for Agriculture and Aquaculture", Tennessee Valley Authority.

Department of Defense, 1978. “Engineering Weather Data,” AFM 88-29, TM 5-785, NAUFAC, pp.. 89, Washington, DC.

Johnson, W. C., 1978. "Culture of Freshwater Prawns Using Geothermal Waste Water", Geo-Heat Center, Klamath Falls, OR.

Lauer, B. E., undated. "Heat Transfer Calculations," Handbook reprinted from the Oil and Gas Journal, pp.. 9.

Stoever, H. J., 1941. "Applied Heat Transmission," McGraw-Hill, New York, NY.

Wolf, H., 1983. "Heat Transfer", Harder & Row, New York, NY, pp.. 254.