



Cooling by night radiation from water with evaporation and convection
by Gregory Nixon Cunniff

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE in Aerospace and Mechanical Engineering

Montana State University

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Abstract:

A mathematical expression of the heat transfer involved in the cooling of a pond of water exposed to the night sky under varying wind velocity, air temperature, vapor concentration, and cloud cover and cloud height was obtained from the turbulent boundary layer equations, and an empirical equation was used to predict the radiant energy exchange between the pond and the night sky.

An experimental test of the proposed equations showed agreement between the predicted and experimentally measured heat transfer.

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Date

October 28, 1970

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WITH EVAPORATION AND CONVECTION

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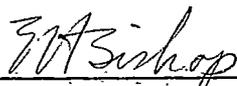
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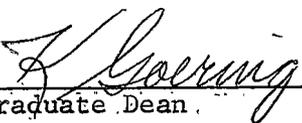
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NOMENCLATURE

Symbol	Description
a	empirical constant
b	empirical constant
c	specific heat at constant pressure, $\text{Btu}/(\text{lb}_m \text{ } ^\circ\text{F})$
C	cloud cover in tenths
d	mass diffusion coefficient, ft^2/sec
\dot{E}''	evaporative mass flux, $\text{lb}_m/(\text{sec ft}^2)$
E_b	black body emissive power, $\text{Btu}/(\text{sec ft}^2)$
g	acceleration of gravity, ft/sec^2
G	irradiation, $\text{Btu}/(\text{sec ft}^2)$
Gr	Grashof number, $\text{Gr} = L^3 g \beta (t_o - t_\infty) / \nu^2$
h	cloud height in thousands of feet
i	enthalpy, Btu/lb_m
i_{fg}	heat of vaporization, Btu/lb_m
I	intensity of radiation, $\text{Btu}/(\text{sec ft}^2 \text{ solid angle})$
J	radiosity, $\text{Btu}/(\text{sec ft}^2)$
k	thermal conductivity, $\text{Btu}/(\text{sec ft}^2 \text{ } ^\circ\text{F}/\text{ft})$
k_λ	monochromatic absorption coefficient
L	length of pond, ft
Le	Lewis number, $\text{Le} = d/\alpha$
m	vapor concentration, lb_m/ft^3

Symbol	Description
p	pressure, lb_f/ft^2
P_v	vapor pressure, millibars
Pr	Prandtl number, $Pr = \nu/\alpha$
\dot{q}''	heat flux, $\text{Btu}/(\text{sec ft}^2)$
\vec{q}''	heat flux vector, $\text{Btu}/(\text{sec ft}^2)$
$\dot{q}''_{o_{\text{net}}}$	net loss of radiant energy, $\text{Btu}/(\text{sec ft}^2)$
\vec{q}''_R	radiant heat flux vector, $\text{Btu}/(\text{sec ft}^2)$
$\dot{q}''_{o_{\text{Total}}}$	total heat flux, $\text{Btu}/(\text{sec ft}^2)$
Re_L	Reynolds number, $Re = u_\infty L/\nu$
Sc	Schmidt number, $Sc = \nu/d$
t	temperature, $^\circ\text{F}$
T	absolute temperature, $^\circ\text{R}$
u	velocity in x-direction, ft/sec
v	velocity in y-direction, ft/sec
w	velocity in z-direction, ft/sec
x	distance from leading edge, ft
y	vertical distance from water surface, ft
z	distance parallel to leading edge
Greek Symbols	Description
α	thermal diffusivity, $\alpha = k/\rho c$, ft^2/sec
β	thermal expansion coefficient, $1/^\circ\text{R}$
β_λ	monochromatic extinction coefficient

Greek Symbols	Description
$\frac{D}{D\theta}$	substantial derivative, $\frac{D}{D\theta} = \frac{\partial}{\partial \theta} + u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y} + w \frac{\partial}{\partial z}$
∇	del operator, $\nabla = \frac{\partial}{\partial x} \vec{i} + \frac{\partial}{\partial y} \vec{j} + \frac{\partial}{\partial z} \vec{k}$
ϵ	emmissivity
ϵ_M	eddy diffusivity for momentum, ft^2/sec
ϵ_H	eddy diffusivity for heat, ft^2/sec
ϵ_D	eddy diffusivity for mass, ft^2/sec
γ_λ	monochromatic absorption coefficient
μ	viscosity, $\text{lb}_m/(\text{sec ft})$
ν	kinematic viscosity, ft^2/sec
ϕ	dissipation function (10)
ρ	fluid density, lb_m/ft^3 , (eq. 1)
ρ	reflectivity (eq. 17)
σ	Stefan-Boltzman constant, $\text{Btu}/(\text{sec ft}^2 \text{ } ^\circ\text{R}^4)$
θ	time, sec

Subscripts	Description
∞	refers to conditions in the free stream
j	refers to component j of the mixture
L	based upon the length of pond
λ	refers to monochromatic conditions

x

Subscripts

Description

- | | |
|---|---|
| o | refers to conditions at the water-air interface |
| x | based upon distance from the leading edge |

ABSTRACT

A mathematical expression of the heat transfer involved in the cooling of a pond of water exposed to the night sky under varying wind velocity, air temperature, vapor concentration, and cloud cover and cloud height was obtained from the turbulent boundary layer equations, and an empirical equation was used to predict the radiant energy exchange between the pond and the night sky.

An experimental test of the proposed equations showed agreement between the predicted and experimentally measured heat transfer.

INTRODUCTION

Maintaining a habitable environment is one of the prime considerations in the design and use of any building or fallout shelter.

In the analysis of a fallout shelter, an acceptable environment with respect to gas concentrations and effective temperature can sometimes be maintained by ventilation with outside air only (18). However, in a large number of shelters and in most structures not under emergency conditions another means of conditioning the space must be found.

At the present time there are only a few practical and economical systems that can be used to condition a structure. Among these are (18):

1. Mechanical air conditioning;
2. Well water cooling;
3. Evaporative cooling;
4. Dehumidification by means of a chemical dessicant;
5. Cooling by night radiation from water with evaporation and convection (sometimes referred to as natural air conditioning).

The first system is the most reliable, but its cost for use in a shelter that one hopes is never used is difficult to justify. This system is also expensive in any commercial application. Well water

cooling can also be expensive due to the cost of drilling. In addition, chemical treatment of the water is frequently required. Also, maintaining a consistent flow rate is often not possible. Evaporative cooling is not very effective in humid regions and requires considerable maintenance. Dehumidification lowers the humidity, but if the resulting latent heat that is converted to sensible heat is not removed the effective temperature can actually be increased rather than decreased.

The last system, cooling by night radiation from water with evaporation and convection, can be utilized by exposing a pond of water to the night sky and using the cooled water to condition a building or shelter throughout the day. The ponds could be roof ponds as proposed by Hay and Yellot (8) or for an underground shelter, water could be placed in an above-ground pond. Thus, if the heat transfer between a pond and the night sky could be quantitatively predicted this system would be very economical in comparison to standard air conditioning systems.

The purpose of this thesis is then to develop a means to quantitatively predict the heat transfer from a pond of water exposed to the night sky.

LITERATURE REVIEW

Several investigators have attempted to use night radiation to air condition a residence. Yanagimachi (26) has built several houses in Japan that use solar energy for heating and night radiation for cooling. Bliss (2) used these same principles in a building in Tucson, Arizona. Thomason (21) also constructed two solar houses in Washington, D. C. He noted the decreased heat transfer rates under humid and cloudy conditions. The other investigators also noted some difficulties in radiation cooling.

Recently, Hay and Yellot (6, 7, 8, 25) reported success with a system employing roof ponds and movable insulation. Their system is also very economical in comparison to the standard methods of air conditioning. Their experimental work was conducted in Phoenix, Arizona. In addition, Yellot (24) demonstrated the effectiveness of roof cooling with intermittent water sprays.

In these studies the deficiency in performance of the systems is a result of not being able to quantitatively predict the heat transfer rates under existing meteorological conditions.

There have been several studies of atmospheric radiation in recent years. An analysis of the atmospheric heat balance was conducted by London (11). In the Lake Hefner Studies (22), an empirical equation was developed that related long wavelength atmospheric radiation to local

water vapor pressure, air temperature, and cloud cover and height. The report indicates that the emissivity of water is independent of water temperature and composition and is given as 0.970 ± 0.005 .

Evaporation studies have been carried out by a number of investigators. Deardorff (5) and Sverdrup (20) attempted to correlate evaporation rates as a linear relationship of wind velocities. Millar (13), Hickox (9), Powell (15), and others found a nonlinear relationship between evaporation and wind velocity. Powell and Hickox also noted that evaporation rates are almost unaffected by composition of the water or the type of surface at the water air interface as long as the surface is saturated. Roll (16), Pasquill (14), and Sverdrup (20) also discuss the equality of the eddy diffusivities of heat and mass transfer in finding evaporation rates. Marciano and Harbeck (22), Ahmsbrak (1), and Budyko et al (4) have used a ratio derived by Bowen (3) that expresses the ratio of heat loss by convection to that by evaporation. Yamamoto (26) conducted evaporation studies from pans. He compared his experimental results to an approximate solution of the boundary layer equations and found them to be in good agreement.

Convection heat transfer has been treated in a manner similar to that described for evaporation.

THEORETICAL ANALYSIS

In considering the energy transport between a pond of water and the night sky, there will in general be momentum, temperature, and moisture boundary layers on the surface of the water as shown in Figure 1.

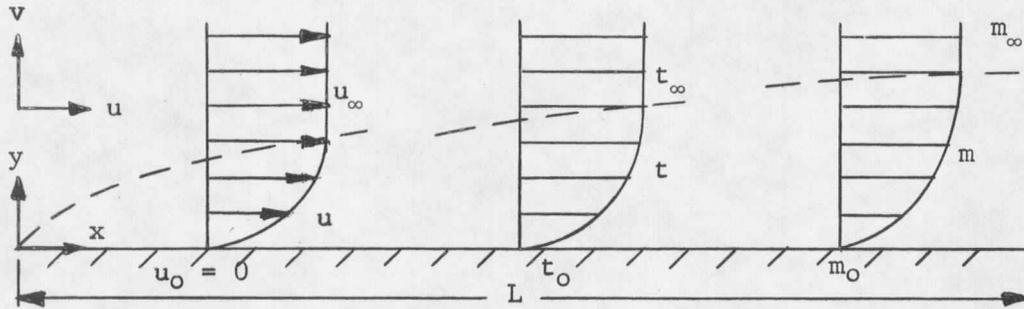


Figure 1. Boundary layer development

The governing conservation of energy equation applied to a moving fluid element may be expressed as (19):

$$\rho \frac{Di}{D\theta} = -\nabla \cdot \vec{q}'' + \nabla \cdot \left(\sum_j d_j i_j \nabla m_j \right) + \mu\phi + \frac{Dp}{D\theta} + s \quad (1)$$

where the left-hand side of the equation represents the rate of change of internal energy of the element. The first term on the right-hand

side is the net heat addition to the element where \vec{q} is the heat flux vector. For a fluid that absorbs, emits and scatters radiation, the heat flux vector will be given by

$$\vec{q}'' = -k \nabla t + \vec{q}''_R$$

where the $k\nabla t$ term represents thermal conduction and \vec{q}''_R is the radiant heat flux vector. The second term on the right-hand side of equation (1) is the transport of energy as a result of the enthalpy of each component's undergoing diffusion. The third term, $\mu\phi$, is the energy dissipated by viscous action that is transformed into heat, where ϕ is the dissipation function. The $\frac{Dp}{D\theta}$ term is the reversible compression work done on the element, and the last term represents any source functions such as internal heat generation.

The structure of the energy equation indicates that the transport mechanisms are coupled, i.e., one process may affect the remaining transport processes. By assuming the transport mechanisms to act independently the resulting equations can be solved. The governing differential boundary layer equations from Schlichting (17) and Kays (10) for steady state, incompressible, constant property turbulent flow are:

Conservation of mass,

$$u \frac{\partial u}{\partial x} + v \frac{\partial v}{\partial y} = 0 \quad (3)$$

Conservation of momentum,

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = \frac{\partial}{\partial y} \left[(\nu + \epsilon_M) \frac{\partial u}{\partial y} \right] \quad (4)$$

Conservation of energy,

$$u \frac{\partial t}{\partial x} + v \frac{\partial t}{\partial y} = \frac{\partial}{\partial y} \left[(\alpha + \epsilon_H) \frac{\partial t}{\partial y} \right] \quad (5)$$

Diffusion,

$$u \frac{\partial m}{\partial x} + v \frac{\partial m}{\partial y} = \frac{\partial}{\partial y} \left[(d + \epsilon_D) \frac{\partial m}{\partial y} \right] \quad (6)$$

where ϵ_M , ϵ_H and ϵ_D are respectively the eddy diffusivities of momentum, heat, and diffusion. The boundary conditions for constant free stream velocity, temperature, and vapor concentration are:

at $y = 0$:

$$u = 0$$

$$v = 0$$

$$t = t_o$$

$$m = m_0$$

as $y \rightarrow \infty$:

$$u \rightarrow u_\infty$$

$$t \rightarrow t_\infty$$

$$m \rightarrow m_\infty$$

at $x = 0$:

$$t = t_\infty$$

$$m = m_\infty$$

The solution to (5) for the local heat transfer rate in the Prandtl number range of gases is given by Kays (10) as

$$\dot{q}''_{0,x} = 0.0295 \rho c u_\infty \text{Pr}^{-0.4} \text{Re}_x^{-0.2} (t_0 - t_\infty) \quad (7)$$

Since the differential equations for energy and diffusion are the same their solutions will also be the same. Thus, for the local evaporation rate

$$\dot{E}''_{0,x} = 0.0295 u_\infty \text{Pr}^{-0.4} \text{Re}_x^{-0.2} (m_0 - m_\infty) \quad (8)$$

The corresponding mean rates of heat transfer and evaporation are

$$\dot{q}''_o = 0.0369 \rho c u_\infty \text{Pr}^{-0.4} \text{Re}_L^{-0.2} (t_o - t_\infty) \quad (9)$$

$$\dot{E}''_o = 0.0369 u_\infty \text{Pr}^{-0.4} \text{Re}_L^{-0.2} (m_o - m_\infty) \quad (10)$$

Equation (10) for the mean rate of evaporation is in very good agreement with the work of Yamamoto (26) who correlated data by Millar (13) and presents the following equation:

$$\dot{E}''_o = 0.042 u_\infty \text{Re}_L^{-0.2} (m_o - m_\infty) \quad (11)$$

If the Prandtl number for air is taken as 0.72 equation (10) reduces to

$$\dot{E}''_o = 0.0421 u_\infty \text{Re}_L^{-0.2} (m_o - m_\infty) \quad (12)$$

Energy transport due to natural convection must also be considered. McAdams (12) recommends the following equations for the mean heat transfer rate from a horizontal plate for natural convection

For $10^5 < \text{Gr Pr} < 2 \times 10^7$

$$\dot{q}''_o = 0.54(k/L) (\text{Gr Pr})^{0.25} (t_o - t_\infty) \quad (13)$$

and for $2 \times 10^7 < Gr Pr < 10^{10}$

$$\dot{q}''_o = 0.14 (k/L) (Gr Pr)^{0.25} (t_o - t_\infty) \quad (14)$$

The mean rate of evaporation due to natural convection is given by Yamamoto (26) as

$$\dot{E}''_o = 0.525 (d/L) (Gr Sc)^{0.25} (m_o - m_\infty) \quad (15)$$

The two mechanisms of energy transport, forced and natural convection, are coupled, but again they will be treated independently.

The transport of energy in the absence of wind will be neglected since energy transport by molecular diffusion is several orders of magnitude less than energy transport by other mechanisms (22). During the experimental studies, observations of "zero" wind were rare and never lasted for more than a few minutes. In addition, the threshold velocity of the anemometer used in the experimental tests was about 0.4 ft/sec. so that a recording of "zero" wind indicates only a velocity less than 0.4 ft/sec. and not necessarily truly zero velocity. Therefore, there is sufficient reason to ignore the case of zero wind.

In considering if the boundary layer is turbulent or laminar, Yamamoto's (26) analysis of Millar's (13) data for evaporation indicated

that the turbulent solution fit the data for a Reynolds number as low as 10,000. Yamamoto's own data showed a transition Reynolds number from laminar to turbulent flow of 50,000. Yamamoto attributed Millar's results to the fact that the rim of the water container used in Millar's experiment was higher than the water surface whereas Yamamoto used a saturated blotter mounted evenly with the edge of the evaporating pan. Thus, the turbulent solution would appear to fit Millar's data for a lower Reynolds number, because of the disturbance caused by the rim. The ponds used in the experimental tests conducted by the author also had a rim above the water surface as would be expected in a practical design. The lowest Reynolds number observed by the author for a fifteen minute average of wind velocity of 1.37 ft/sec. and a pond length of 5 ft. was 38,000. Thus, only the turbulent solution to the boundary layer equations was used in examining the experimental data.

The net exchange of radiant energy as given by Wiebelt (23) can be found by taking an energy balance on an imaginary plane just above the water surface as shown in Figure 2. The incoming radiation or irradiation is designated by G and the radiation leaving the surface or radiosity is designated as J .

The net rate of radiant energy leaving the surface is then given by

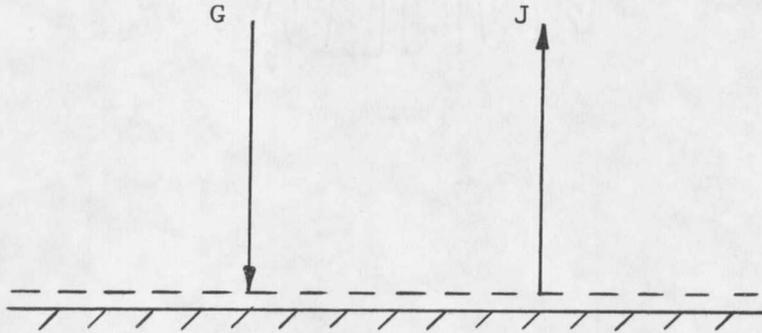


Figure 2

$$\dot{q}''_{o_{net}} = J - G \quad (16)$$

The radiosity is given by

$$J = \rho G + \epsilon E_b \quad (17)$$

where ρ is the reflectivity, given by one minus the emissivity, ϵ , and E_b is the black body emissive power of the surface as given by the Stefan-Boltzman law

$$E_b = \sigma T^4 \quad (18)$$

where σ is the Stefan-Boltzman constant. The solution to the net exchange of radiant energy requires a knowledge of the irradiation since all other terms can be found.

Consider a monochromatic beam of initial radiation intensity $I_{o\lambda}$ passing through a control volume as shown in Figure 3.

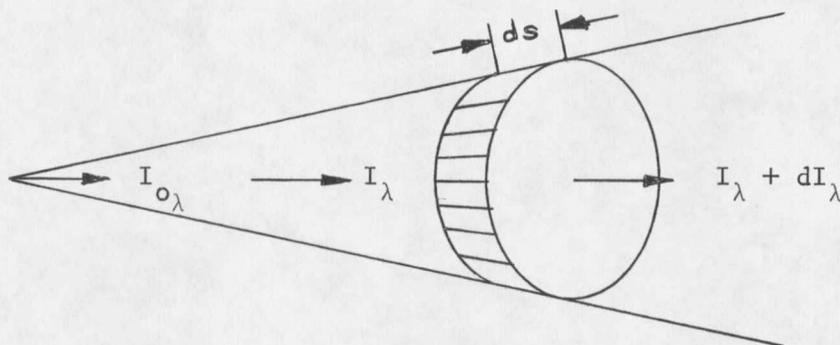


Figure 3. Control volume for participating medium

As a result of traversing the length ds the beam will undergo attenuation by scattering and absorption. The amount of absorption can be assumed to be directly proportional to the incident intensity, I_{λ} , and the path length ds . The amount of absorption can then be expressed as

$$k_{\lambda} I_{\lambda} ds$$

where k_λ is the monochromatic absorption coefficient. Scattering can be considered analogous to absorption with the amount of scattering given by

$$\gamma_\lambda I_\lambda ds$$

where γ_λ is the monochromatic scattering coefficient. The total attenuation is given as

$$dI_\lambda = -k_\lambda I_\lambda ds - \gamma_\lambda I_\lambda ds$$

or defining the extinction coefficient β_λ as

$$\beta_\lambda = k_\lambda + \gamma_\lambda \tag{19}$$

the attenuation becomes

$$dI_\lambda = -\beta_\lambda I_\lambda ds$$

Integrating yields

$$I_\lambda = I_{o_\lambda} e^{-\int \beta_\lambda ds} \tag{20}$$

Thus the evaluation of the irradiation term in the energy balance requires a knowledge of the extinction coefficient, which is a function of the distribution of the constituents in the atmosphere that participate in the radiant energy exchange. Since the distribution of the atmospheric components which scatter, absorb, and emit radiation is difficult to define, the evaluation of an atmospheric extinction coefficient is difficult at best.

For this reason an empirical equation proposed in the Lake Hefner Studies (22) was used to evaluate the atmospheric radiation or irradiation. This equation relates the local water vapor pressure, air temperature, and cloud cover and height to the atmospheric radiation. The equation is given by

$$G = \sigma T_{\infty}^4 (a + bp_v) \quad (21)$$

where T_{∞} and p_v are respectively the air temperature and vapor pressure in millibars at a height of two meters. The two empirical constants a and b are given by

$$a = 0.740 + 0.025 C e^{-0.0584h}$$

$$b = 0.00490 - 0.00054 C e^{-0.060h}$$

where C is the amount of cloud cover in tenths and h is the height of the clouds in thousands of feet. Clouds below 1600 feet must be considered equal to clouds at 1600 feet. The report states that a vapor pressure representing the total atmospheric content rather than the local vapor pressure should be used in the empirical correlation. For this reason the equation should be used only in areas with an air mass structure similar to that of Lake Hefner. However, London (11) indicates that for average cloudiness the variation in net long-wavelength radiation from Earth, $\dot{q}''_{o_{net}}$, between 0° and 50° north latitude is about 10%. On this basis equation (21) was used to evaluate the atmospheric radiation to be used in equation (16).

Therefore, the total energy loss by the pond can be found by adding the convective heat transfer rate plus the evaporation rate times the heat of vaporization plus the net radiant energy leaving the surface:

$$\dot{q}''_{o_{Total}} = \dot{q}''_o + \dot{E}''_o (i_{fg}) + \dot{q}''_{o_{net}} \quad (22)$$

EXPERIMENTAL APPARATUS AND PROCEDURES

The basic procedure was to measure the actual experimental heat loss from two different ponds of water and then to compare this with the loss predicted by semi-empirical equations using atmospheric data.

Two ponds were constructed near Belgrade, Montana, at an FAA installation to test the proposed equations. The site was chosen because of security and openness of terrain. The ponds were constructed of three-inch Styrofoam and lined with black polyethylene plastic. One pond was five feet square, and the other was seven feet square. Both ponds were six inches deep filled with water to a depth of approximately five inches.

Air temperature and relative humidity were recorded continuously on a Weather Measure hygrothermograph. Wind velocity and direction were measured by means of a six-cup anemometer and vane leased from the Weather Measure Corporation. The two instruments had a threshold velocity of approximately 0.4 ft/sec. The DC outputs from the anemometer and vane were recorded continuously on a Varian dual channel strip chart recorder. The air temperature, relative humidity, wind velocity, and wind direction readings were all taken at a height of 2 meters.

Cloud cover and cloud height data were obtained from hourly readings taken by FAA personnel located at Gallatin Field near Belgrade. Barometric pressure was also taken from FAA data.

In order to measure the change in internal energy of the pond, water a bulk or mixing-cup temperature was needed. The smallest pond was divided into nine grid squares and three copper-constantan thermocouples were placed at the bottom, middle, and surface of the water at the midpoint of each grid square. These three thermocouples were connected in parallel to give an average temperature at the midpoint of each grid square. The nine midpoint averages were then connected in parallel to give one average reading for the pond. At the center of the pond five thermocouples were evenly placed across the depth of the pond and the resulting readings averaged to give a comparison against the 27 thermocouples placed at the midpoints of the nine grid squares. The two averages (in °F) agreed to within less than 2% deviation so that the bulk temperature of the larger pond was taken by the five thermocouples placed at the center of the pond.

This same procedure was carried out to obtain an average surface temperature, and again the temperature at the center of the pond was found to agree to within less than 2% deviation with the average of the nine surface grid midpoints.

The average temperature of the inside and outside of the sides and bottom of the pond was treated in a similar manner so the heat transfer by conduction through the sides and bottom could be accounted for in the data analysis.

All temperatures were recorded on a Honeywell 24 point recording potentiometer with a cycling rate of 40 sec. The temperature recorder was calibrated by means of a Honeywell potentiometer.

The experimental setup is shown in Figure 4.

Since the equations developed for prediction of the energy loss were for steady-state flow, a type of finite difference technique was used in computing the needed parameters from the atmospheric data. All properties and parameters required in the solution were time-averaged over an interval of time. All properties of the vapor-air mixture were evaluated at the film temperature, i.e., the average of the surface temperature and air temperature. These time-averaged values for the parameters were then used in the steady state solution to obtain the predicted total energy loss for the interval. The bulk temperature at the beginning of each interval was used as the average surface temperature for the interval. The energy loss was computed and the resultant calculated drop in pond temperature was used to find the bulk temperature at the end of the interval. This temperature was then used as the average bulk temperature for the succeeding interval.

Interval lengths of 15 minutes and of 2 minutes were used in analysis of the data. The computed change in internal energy was then compared to the measured change in internal energy for every hour, and an hourly deviation was computed. A total deviation for an entire

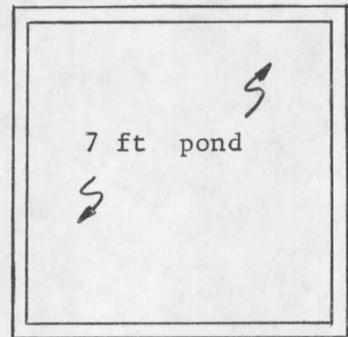
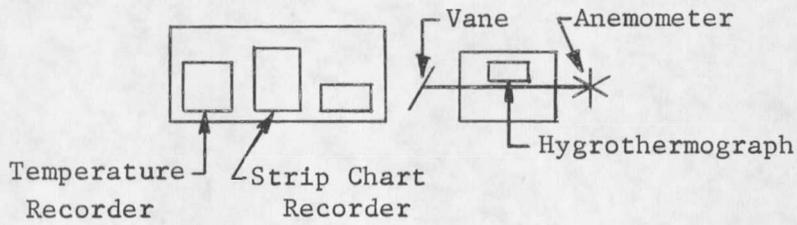
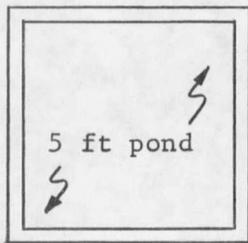


Figure 4. Experimental setup

night was also computed.

Data reduction and analysis were done through the use of a computer program run on an XDS computer.

EXPERIMENTAL RESULTS

Analysis of the hourly deviations between calculated and experimental energy losses ($\% = \frac{\text{exp.} - \text{calc.}}{\text{exp.}} \times 100$) using the 15-minute intervals showed an average hourly deviation of 17%. Table 1 gives the distribution of these deviations.

Table 1. Distribution of hourly deviations for 15-minute intervals.

<u>Per Cent of Predicted Results</u>	within	<u>Per Cent of Experimental Results</u>
12		5
24		10
47		15
62		20
76		25
90		30

Analysis was also made for entire nights using 15-minute intervals. This showed an average nightly deviation of 14%. Table 2 gives the distribution of these deviations.

Table 2. Distribution of nightly deviations for 15-minute intervals.

<u>Per Cent of Predicted Results</u>	within	<u>Per Cent of Experimental Results</u>
14		5
21		10
57		15
79		20
86		25
100		30

Results for the 2-minute intervals, as shown in Tables 3 and 4, were practically the same as those for the 15-minute intervals, indicating no increase in accuracy by using the smaller interval.

Table 3. Distribution of hourly deviations for 2-minute intervals.

<u>Per Cent of Predicted Results</u>	within	<u>Per Cent of Experimental Results</u>
10		5
19		10
43		15
62		20

Table 3 (con't)

<u>Per Cent of Predicted Results</u>	within	<u>Per Cent of Experimental Results</u>
75		25
87		30

Table 4. Distribution of nightly deviations for
2-minute intervals.

<u>Per Cent of Predicted Results</u>	within	<u>Per Cent of Experimental Results</u>
14		5
14		10
50		15
79		20
86		25
100		30

A noteworthy point is that approximately 90% of the deviations were positive, indicating that the predicted energy loss was low. This result is in part due to the fact that the free stream velocity, air temperature, and vapor concentration measurements were probably not taken outside the boundary layers. In the Lake Hafner Studies (22) these measurements were taken at a height of 8 meters. Sverdrup (20)

shows a similar result, and his data further indicate that the temperature and concentration boundary layers are approximately the same thickness. Some investigators have used 5 meters as the level of these measurements, while others have used the 2 meter level. If the 5 or 8 meter level had been used in the present study the wind velocities would have been greater resulting in smaller deviations between the measured and computed energy losses.

The present analysis does not take into account the disturbance of the water surface from wave formation. However, ripples on the surface were not frequently observed.

CONCLUSIONS

By use of equation (22) it can be expected that predicted heat transfer from a pond to the night sky will average to within 14% of true values, with a maximum deviation of 28%.

It is recommended that free stream conditions to be used in these equations be measured at a height of at least 8 meters to improve the accuracy of the predictions.

APPENDIX I

Equipment List

Cup Anemometer - Model W103; Manufactured by Weather Measure Corporation;
Sacramento, California.

Vane - Model W104; Manufactured by Weather Measure Corporation,
Sacramento, California.

Translator for Anemometer and Vane - Model W1034-360; Low Range-50 mph/
volt, High Range-100 mph/volt; Manufactured by Weather
Measure Corporation; Sacramento, California.

Hygrothermograph - Model H-311; Serial 131; Manufactured by Weather
Measure Corporation; Sacramento, California

Strip Chart Recorder - Model G-2025; Serial 2260; Manufactured by
Varian Aerograph; Walnut Creek, California.

Temperature Recorder - Model 212-270; Serial 04684092001; Manufactured
by Honeywell; Denver, Colorado.

Potentiometer - Model 2745; Serial P-2353; Manufactured by Honeywell;
Denver, Colorado.

APPENDIX II

Sample Experimental Data

for

September 20, 1970 (2:00 a.m. - 2:30 a.m.)

(Complete data for the entire test are contained on strip chart recordings on file in the Aerospace and Mechanical Engineering Department, Montana State University, Bozeman, Montana 59715)

Experimental Data for September 20, 1970

Interval from 2:00 a.m. - 2:15 a.m.

Bulk temp., °F	48.2 48.2 48.0 48.0 47.8 47.7 47.5 47.4
Surface temp., °F	48.8 48.7 48.6 48.5 48.3 48.2 48.0 48.0
Side Inside temp., °F	47.0
Side Outside temp., °F	30.0
Bottom Inside temp., °F	50.0
Bottom Outside temp., °F	35.0
Air temp., °F	36.0
Relative Humidity, %	85.0
Wind Velocity Voltage, 25 mph/volt	0.17 0.15 0.15 0.13 0.12 0.13 0.13 0.13
Cloud Cover, tenths	0.0
Cloud Height, ft	0.0
Pond Length, ft	5.0
Pond Depth, in.	5.75
Barometric Pressure, in. Hg	25.51

Experimental Data for September 20, 1970

Interval from 2:15 a.m. - 2:30 a.m.

Bulk temp., °F	47.6 47.5 47.5 47.2 47.0 47.0 47.0 46.8
Surface temp., °F	48.0 48.6 47.5 47.4 47.5 47.2 47.2 47.6
Side Inside temp., °F	47.0
Side Outside temp., °F	30.0
Bottom Inside temp., °F	50.0
Bottom Outside temp., °F	35.0
Air temp., °F	36.2
Relative Humidity, %	86.0
Wind Velocity Voltage, 25 mph/volt	0.15 0.10 0.15 0.17 0.18 0.14 0.10 0.10
Cloud Cover, tenths	0.0
Cloud Height, ft	0.0
Pond Length, ft	5.0
Pond Depth, in.	5.75
Barometric Pressure, in. Hg	25.51

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