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AN ACCURATE UPPER ESTIMATE FOR THE TRANSMISSION OF SOLAR RADIATION IN SALT GRADIENT PONDS

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Abstract—The objective of the present work is the estimation of maximum transmission of solar radiation within a body of natural water under the most favorable conditions, with special reference to salt gradient solar ponds.

The study, based on recent data, includes two alternative analytical approaches based on the split of the solar spectrum into the appropriate number of spectral bands and numerical calculation of discrete values of integrals according to Beer's law. As far as radiation transmission properties of clear water are concerned, it was found that the broadly used absorption law, which is commonly referred to as an upper transmission limit, is derived from original work by Schmidt[23] and deficient data, employed at the time, are responsible for the appreciably lower theoretical maximum transmission then derived. The accurate upper transmission limit derived now also gives comparative higher heat collection efficiency. Comments have been made for the introduction of a water clarity dimensionless factor in terms of the upper transmission limit, describing the economical operation limits for solar pond water.

1. INTRODUCTION

The transmission of solar radiation in salt gradient solar ponds is an important research topic, as better transmission through the pond water leads to proportionally more heat being collected at the lower convecting zone. However, even though the stagnant mass of the salt-stratified brine provides very good thermal insulation, its fundamentally poor radiation transmission properties are responsible for relatively low heat collection efficiencies.

The earlier investigations involved the estimation of solar radiation transmission in natural waters for applications in oceanography, as the underwater light greatly affects the life in the oceans and, more recently, for water pollution control in natural lakes and reservoirs. The need for a typical radiation transmission model for solar pond research applications has motivated various recent investigators to reassess the previous work and to develop simple methods to describe solar energy absorption within the pond waters.

The derived four exponential term transmission function that was suggested by Rabl and Nielsen[1], was based on earlier calculations on distilled water data and was extensively employed in solar pond performance predictions. It has become known as an upper transmission limit to solar radiation, as the pond waters never would be expected as clear as distilled water.

Therefore, very high transmission measurements[2] that appeared sporadically in the literature and recent calculations—also based on distilled water data—showed appreciably higher transmission conditions. This is found to be in open conflict with the widely employed four exponential term transmission function.

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The aim of this work is to give reasonable explanations to the discrepancies found between previous analyses and measurements, to calculate accurately an upper theoretical transmission limit, and to examine its implications to the calculated thermal performance.

2. BACKGROUND THEORY

Solar energy radiation, penetrating the surface of a body of natural water, will suffer a decrease in intensity as a result of absorption and scattering of energy by pure water and suspended and dissolved matter.

Although absorbed energy is transformed mainly to heat and, to a small extent, to chemical energy, scattering, which is caused by reflection and diffraction at small particles and colloidal solutions, is responsible for changing the direction of light and can be noticed by an observer outside the path of direct light rays as Tyndall light.

The intensity of scattered light is proportional to s/λ^n, where s is the volume concentration of scatterers. When size of scattering particles is small compared to the wavelength λ, then $n = 4$ (Rayleigh scattering), otherwise $n < 4$.

The scattering of light in optically pure water is due to the Brownian motion of water molecules, which causes very small density fluctuations and therefore optical inhomogeneities in the water, which lead to irregular variations of light refraction in spaces of molecular size[3]. Each of the above phenomena, which independently contributes to the decrease of radiation intensity, is characterized by an extinction coefficient that is strongly wavelength dependent, and the overall extinction of radiation phenomenon is described by the wavelength-dependent extinction coefficient:

$$E(\lambda) = k(\lambda) + \varepsilon(\lambda) + k_w(\lambda) + \varepsilon_w(\lambda)$$

where k and k_w denote absorption by pure water and by suspended and dissolved matter, respectively, and ε, ε_w denote scattering by pure water and by suspended and dissolved matter, respectively.

It is possible to define the average extinction coefficient E for the total radiated energy, although it should be kept in mind that the solar spectrum penetrating the water body undergoes a dramatic change in spectral composition.

Mathematically, radiation extinction is described at a certain wavelength λ by Beer's law

$$B(\lambda,x) = B(\lambda,0)\cdot\exp[-E(\lambda)\cdot x]$$

where $B(\lambda,0)$ is the energy in the solar spectrum at the wavelength λ at $x = 0$, (just below the free liquid surface), when x is the optical depth or the depth in the pond with zero angle of incidence (sun overhead). $B(\lambda,x)$ is the transmitted energy at depth x and $E(\lambda)$ is the extinction coefficient that includes both phenomena, absorption, and scattering at wavelength λ. Then the total energy of the solar spectrum at the depth x is given by

$$\begin{aligned} B(x) &= \int_0^\infty B(\lambda,x)\cdot d\lambda \\ &= \int_0^\infty B(\lambda,0)\cdot\exp[-E(\lambda)\cdot x]\cdot d\lambda \end{aligned}$$

and if the solar spectral irradiance is considered over a definite wavelength range of interest, as is usually happens in solar pond research,

$$B(x) = \int_{\lambda_{min}}^{\lambda_{max}} B(\lambda,0)\cdot\exp[-E(\lambda)\cdot x]\cdot d\lambda \quad (1)$$

It is well known that, although the existence of dissolved salts in small concentrations in pure water does not appreciably affect transmission of radiation, the highly concentrated brines, especially near the bottom of salt gradient solar ponds where the solution is near saturation, seems to affect radiation transmission considerably.

Previously reported work from Usmanov et al.[4] and Lund and Keinonen[5] have shown that function E is also concentration dependent and, consequently, depth dependent. It must be noted here though, that Usmanov's extinction data for pure water were found to be appreciably higher than those in the literature at the range between 0.36 and 0.6 μ.

The extinction of monochromatic radiation in a water layer dx at a depth x from the surface of a solar pond, in which the salt concentration varies linearly with zero salinity concentration at the top, is

$$dB(\lambda,x) = -E(\lambda,x)\cdot B(\lambda,x)\cdot dx$$

and integrating we have,

$$\ln B(\lambda,x) = -\int_0^x E(\lambda,x)\cdot dx + C$$

from the condition, at $x = 0$, $B(\lambda,x) = B(\lambda,0)$, the numerical constant is derived and the expression becomes

$$B(\lambda,x) = B(\lambda,0)\cdot\exp\left[-\int_0^x E(\lambda,x)\cdot dx\right]$$

The total energy of the spectrum of interest between λ_{min} and λ_{max} at depth x is given by

$$B(x) = \int_{\lambda_{min}}^{\lambda_{max}} B(\lambda,0)\cdot\exp\left[-\int_0^x E(\lambda,x)\cdot dx\right]\cdot d\lambda \quad (2)$$

Distinct values of both integrals (1) and (2) give the exact values of the transmitted solar radiation at a given depth x. The functions $B(\lambda,0)$, $E(\lambda)$, and $E(\lambda,x)$ are given graphically or in tabular data form and the integrals can be computed numerically.

To avoid numerical methods, a less complicated, although less accurate approach is offered for the calculation of transmission at a given depth, as a contribution of energy transmission from various portions of the solar spectrum, which is divided into a number of wavelength bands $\lambda_1, \lambda_2, \lambda_3, \ldots, \lambda_N, \lambda_{N+1}$, according to the mean value of the extinction coefficient in each band.

Then,

$$B(x) = \sum_{i=1}^{N} \bar{B}_i\cdot e^{-\bar{E}_i\cdot x}$$

where

$$\bar{B}_i = \frac{\int_{\lambda_i}^{\lambda_{i+1}} B(\lambda)\cdot d\lambda}{\int_{\lambda_i}^{\lambda_{i+1}} d\lambda} \quad \text{and} \quad \bar{E}_i = \frac{\int_{\lambda_i}^{\lambda_{i+1}} E(\lambda)\cdot d\lambda}{\int_{\lambda_i}^{\lambda_{i+1}} d\lambda}$$

If the total energy content of solar spectrum is

$$\bar{B} = \int_{\lambda_i}^{\lambda_{i+1}} B(\lambda)\cdot d\lambda$$

per unit transmission may be defined as the ratio

$$TR(x) = \frac{B(x)}{\bar{B}}$$

Obviously, a calculation with a larger number of bands gives more accurate results.

3. AVAILABLE DATA AND PREVIOUSLY REPORTED WORK

Since extinction data and solar spectral irradiance data are involved with the calculation of the energy that is transmitted through the body of natural waters, a brief discussion is devoted to both of these, which were derived from spectral measurements.

The solar spectrum at sea level appears appreciably different from blackbody radiation at the same temperature, due mainly to selective absorption of spectrum by various atmospheric gases. Although the direct beam radiation spectrum on a horizontal surface diminishes rapidly with increasing air mass according to Lambert's law, and shifts its energy content toward longer wavelengths (the most favorable case is AM = 1 with the sun nearly overhead), the diffuse spectrum adds considerable energy in the UV region and blue. It is generally believed that the diffuse spectrum due to Rayleigh scattering is shifted toward shorter wavelengths with peaks near 0.33 μ and 0.41 μ and there is good agreement between results from theoretical models and field measurements.

Since incident radiation is composed of direct and diffuse components with vastly different spectral composition, these must be treated separately for the derivation of radiation transmission data and introduction into computer simulation calculations.

Hull[6] suggested a simple means of approximating the transmission of diffuse radiation in solar ponds. He assumed this component as isotropic and he calculated its transmission by splitting the blackbody spectrum at sky color temperature corresponding to various weather types.

However, due to the complexity of the combination of different stochastic variations in the spectral composition of the diffuse radiation spectrum, related to different weather types and clouds, attention is concentrated on transmission of direct radiation. The fact that diffuse radiation is usually a small portion of the total incident solar energy and is characterized by relatively higher reflection losses at the air–water interface, neglecting diffuse radiation with its shorter wavelength content leads to more pessimistic estimation of transmission of solar radiation.

Extensive work has been carried out earlier and more recently from various researchers on the solar constant, spectral distribution of solar radiation, and on the absorption effects of the atmosphere[7–9]. Due to the fact that earlier investigations were based on extrapolation from ground-based observations, recent observations, made from satellites, prove to be more accurate, and Thekaekara proposed a standard solar spectrum at AM = 0 and reported extensive data on solar spectral irradiance at sea level and various air masses[10,11] from which the AM = 1 solar spectrum in tabular form was depicted.

On the other hand, extensive work has been carried out since the late nineteenth century in experimental investigation of spectral extinction coefficients, mainly for doubly distilled water, pure water, and seawater of various origins. In the literature, the term "pure water" usually means extremely carefully filtered clear oceanic water.

More and more careful measurements have been made by Hufner and Albrecht (1891)[12], Aschkinass (1895)[13], Collins (1925)[14], Sawyer (1931)[15], Clarke and James (1939)[16], Curcio and Petty (1951)[17], and others covering a broad band of wavelengths. It has been proved[16] that the optical properties of doubly distilled and pure water are practically the same and the presence of salt in small concentrations does not affect transmission of radiation.

Dietrich[18] has compared and summarized the results of investigations, which were performed for pure water until the late 1930s and presented an extinction curve covering the wavelength range between 0.186 to 2.65 μ, which appears repeatedly in the more recent oceanographical literature[3,19].

The results of several more recent investigations have been reviewed by Hale and Querry[20] and Smith and Baker[21], and the derived data from these investigations scatter slightly around the extinction curve, mainly because it is extremely difficult to obtain a standard quality of "optically pure" water. There is good agreement between older and more recent investigations, especially at wavelengths longer than 0.5 μ. At shorter wavelengths, reported data by Hale and Querry[20] appear higher. Even so, the small differences between various investigators do not greatly affect the shape of the extinction curve.

The most widely known mathematical expression on transmission of solar radiation in the literature is the Rabl and Nielsen (R-N)[1] four exponential term expression, which was approximated by the handy algebraic relationship

$$h(x) = 0 \cdot 36 - 0.08 \cdot \ln x$$

in the range of 10 m $\geq x \geq$ 0.01 m by Bryant and Colbeck[22]. Although not very accurate for the purpose, as it is based on distilled water data, this expression gives an upper theoretical transmission limit on which numerous solar pond performance predictions were based. This expression gives the per unit transmission at certain depth, as a contribution of radiation transmission of each one of the four individual portions of solar spectrum from 0.2 to 0.6 μ, 0.6 to 0.75 μ, 0.75 to 0.9 μ, and 0.9 to 1.2 μ.

According to Rabl and Nielsen, its derivation was based on oceanographical data by Defant[19] which are due to earlier calculations on solar energy deposition at various depths in the body of natural waters by Schmidt[23].

Calculation of Schmidt's tables and diagrams, which can be found in[23], describing the energy transmission at various depths in a water body, were based on spectral extinction measurements by Aschkinass[13] and a solar spectrum at the sea level, which is due to Langley[24] and appears appreciably different from solar spectral irradiance diagrams according to more recent measurements at sea level and AM = 1.

Using recent extinction data, Hull[6] divided the AM = 1 spectrum into a large number of wavelength bands and derived a 40-exponential term, 80-parameter extinction function. He obtained appreciably higher transmission than the values imposed by the previously calculated upper transmission limit and his thermal calculations showed 15 to 20°C higher temperatures, starting from identical initial conditions.

Even though transmission comparisons between 40-term absorption function and recent absorption data from clear lake water have shown good agreement according to Hull, there is no explanation of the difference in transmission between the 40- and 4-term Rabl–Nielsen function, except for the implication that it comes from greater accuracy of 40 terms.

A part from an indication in [25] that the 4-term R–N function was derived from a simple exponential fitting of Defant's data, it is not quite clear from [1] whether it was derived by calculation using extinction coefficient data applied to the spectrum of interest or by simple fitting of Schmidt's data. If it was calculated, it is not known why the divisions were so chosen, as the most of the radiated energy lies within the 0.2 to 0.6-μ range, since at 0.5 μ there is a very sensitive transmittance window with significant variations of the extinction coefficient.

One plausible explanation is that the total radiated energy in Langley's solar spectrum, which was used by Schmidt, is shifted toward longer wavelengths, so that the band 0.2 to 0.6 μ contains appreciably less energy than is now found.

4. THE PRESENT WORK

Using the same four divisions of the solar spectrum, the amplitudes of exponential terms were calculated using the blackbody spectrum at the temperature of 5762 K, a recent AM = 1 solar spectrum at sea level, and Langley's spectrum. The mean extinction coefficients over each band are identical and the results are shown in Table 1. As can be seen, the derived amplitudes for blackbody and AM = 1 spectrum show much the same deviation from the R–N function and are appreciably different from the function widely used, especially in the amplitude of the most deeply penetrating first-term component, which is about 46% higher and greatly affects thermal performance calculations.

The derived amplitudes from Langley's spectrum were found to be very close to those of the R–N transmission function and this very probably means that in its initial derivation the appropriate solar energy spectrum was not used.

Aiming at a more logical division of the spectrum in bands according to the energy content, and the corresponding mean value of extinction coefficient in each band, the spectrum was divided into 19 wavelength bands. The higher the energy content and the smaller extinction coefficient, the narrower the band.

Extinction data are identical to those employed by Hull[26] and, which, according to recommendations of Jerlov[27] have been adapted from measurements made by Clarke and James[16] and Curcio and Petty[17] in the regions between 0.325 to 0.8 μ and 0.8 to 1.3 μ, respectively, and shown by curve 1 in Fig. 1.

Solar spectral irradiance data for the AM = 1 solar spectrum ($\alpha = 0.66$, $\beta = 0.085$) have been adapted from Thekaekara[11] and is shown by curve 2 in Fig. 1, in which the 19 bands are also shown. The so-computed transmission function has the form

$$h(x) = \sum_{i=1}^{19} \mu_i \cdot \exp(-n_i \cdot x)$$

Constants μ_i and n_i, which are given in columns 3 and 5 of Table 2, were calculated according to the presented simplified method in background theory, starting with the AM = 1 solar spectrum as depicted from Thekaekara[11] and with spectral extinction coefficients as depicted from [27]. In column 4 of Table 2, the corresponding amplitudes for each of the 19 bands are given comparatively, according to data from Thekaekara[10] for AM = 0.

To the author's knowledge, although spectral extinction coefficient data are readily available in the literature for distilled water[21,28], apart from the work by Usmanov et al.[4] and Lund and Keinonen[5], which is not suitable for NaCl salt-water solutions, there are very few references to detailed experimental results on extinction measurements in salt solutions of various concentrations in distilled water. Apparently, there is much need for further work toward the accurate experimental determination of detailed spectral extinction characteristics of the commonly employed salts in a range of different concentrations.

Table 1. Exponential term amplitudes, as calculated for various solar energy spectral distributions

Amplitudes	First term	Second term	Third term	Fourth term	Fifth term
Wavelength band	0.2–0.6	0.6–0.75	0.75–0.9	0.9–1.2	1.2–3
Four-exponent term R–N function	0.237	0.193	0.167	0.179	0.224
According to recent AM = 1 spectrum	0.346	0.203	0.128	0.153	0.167
Blackbody spectrum at 5762 K	0.391	0.143	0.119	0.129	0.215
Schmidt's spectrum	0.229	0.196	0.150	0.177	0.246

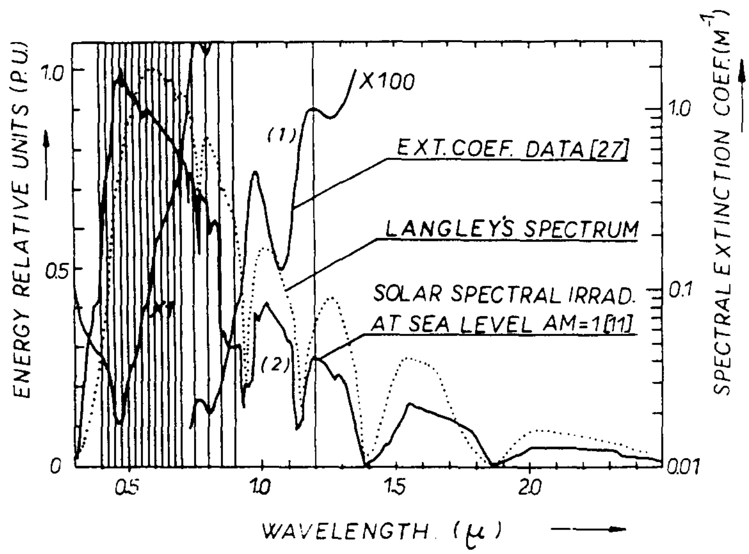

Fig. 1. Division of the AM = 1 solar spectrum at sea level (curve 2), in 19 wavelength bands. Curve 1 shows the shape of the extinction curve according to spectral measurements of extinction coefficient in distilled water.

Accordingly, it seems improbable that numerical calculation of integral (2) can give reliable results. Instead, calculation of (1) is possible from solar spectral irradiance and extinction data in tabular form. Integrals were calculated numerically by a digital computer using the Simpson and Gill–Miller methods. The results from both methods were almost the same with differences less than 0.1%.

For the purpose of integration, it was found that the division of the spectrum of interest into 100 equally spaced bands gives good accuracy, whereas acceptable accuracy could be obtained with only 30 or 40 bands, as can be seen in Fig. 2.

The results of the above calculations are shown in Fig. 3 in which curve 1 represents the derived 19 exponential term transmission function, curve 2 represents the R–N transmission function, curve 3 the transmission function (which was derived by calculation of the integral (1)), and curve 4 represents the almost identical to (3) 40 exponential term Hull's transmission function.

Curves 5 and 6 represent measurements for clear open sea water (Sargasso Sea) as depicted from [29] and from Castle Lake as depicted from [30], respectively. Note that both indicate higher than the four exponential term R–N transmission.

Table 2. Calculated amplitudes and extinction coefficients for the 19-term transmission function

(1)	(2)	(3)	(4)	(5)
		Amplitudes		
N	Wavelength band (μ)	Thekaekara at AM = 1[11]	Thekaekara at AM = 0[10]	Extinction coefficient (m^{-1})[27]
1	0.200–0.400	0.0466	0.0910	.058
2	0.400–0.425	0.0290	0.0346	.039
3	0.425–0.450	0.0345	0.0366	.025
4	0.450–0.475	0.0408	0.0399	.018
5	0.475–0.500	0.0413	0.0383	.026
6	0.500–0.525	0.0400	0.0355	.038
7	0.525–0.550	0.0390	0.0359	.055
8	0.550–0.575	0.0375	0.0350	.081
9	0.575–0.600	0.0375	0.0337	.137
10	0.600–0.625	0.0367	0.0324	.205
11	0.625–0.650	0.0360	0.0306	.255
12	0.650–0.675	0.0350	0.0289	.324
13	0.675–0.700	0.0327	0.0271	.425
14	0.700–0.750	0.0629	0.0494	1.33
15	0.750–0.800	0.0548	0.0439	2.2
16	0.800–0.850	0.0476	0.0390	2.9
17	0.850–0.900	0.0263	0.0346	5.17
18	0.900–1.200	0.1530	0.1495	42.5
19	1.200–3.000	0.1676	0.1832	1800.0

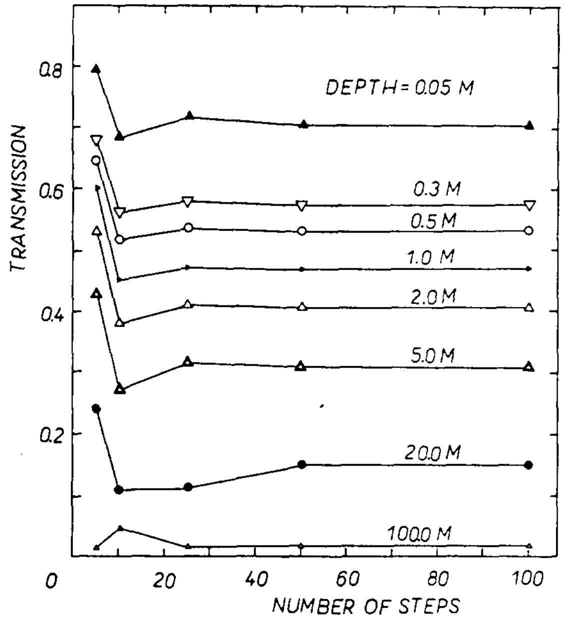

Fig. 2. The effect of the number of the equally spaced bands in the calculated transmission, as it was found for various depths, in the numerical calculation of intergral (1) (Simpson's method).

Curves 7 and 8 represent data from actual solar ponds. Curve 7 represents typical measurements for untreated pond water from the Miamisburg solar pond[31] and curve 8 represents data reported by Tabor and Matz[2] for the Sdom solar pond. It is remarkable to note here the high water transparency near the top surface, which significantly decreases, possibly due to settling of dirt near the bottom of this small-scale experimental pond.

The 19-term transmission function gives comparable transmission (difference less than 2%) with curve 3, which was derived from calculation of the integral (1). In the range of depths between 0 and 0.2 m, which usually correspond to the upper mixing zone thickness with no effect in the calculation of thermal performance, this difference becomes higher (typically less than 4% at 0.1 m) due to the fact that for calculation of the integral (1) the I.R. part of the spectrum at longer wavelengths than 1.3 is excluded.

It can be seen also that the derived results show about 0.1 better transmission at almost any practical depth from the R–N function and are identical to Hull's function.

In the same figure, curve 9 represents the transmission function as calculated from numerical intergration starting from identical spectral extinction coefficient data and Langley's spectrum, whereas calculation starting from AM = 1 and the familiar division of the spectrum into four wavelength bands, gives transmission data closely lying to curve (3). This very probably suggests that while the use of the proper, most favorable AM = 1 spectrum greatly improves the accuracy of calculations, being responsible for the appreciable increase in transmission, the use of coarser or four-band division slightly affects radiation transmission.

The derived function may be fitted by polynomials with high accuracy such as the one of fourth degree,

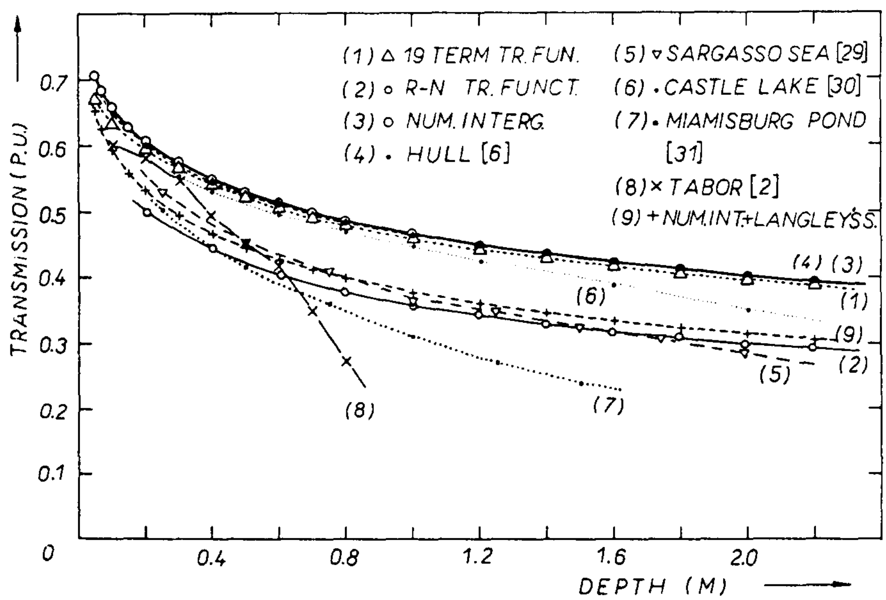

Fig. 3. Comparison between measurements, previous analyses, and derived results. Curve (1) and (3) show the almost identical results that were derived from the 19 exponential term and numerical intergration and (2) the 4 exponential term R–N function. Also shown are (5), (6), (7), and (8) data from measurements. Curve (9) was derived by numerical intergration starting with spectral extinction data from [27] and Langley's spectrum. Curve (4) represent data derived by Hull[6].

$$h(x) = 0.67031 - 0.35170 \cdot x + 0.19785 \cdot x^2 - 0.05567 \cdot x^3 + 0.00580 \cdot x^4$$

and can be approximated with good accuracy by the simple algebraic relationship

$$h(x) = 0.46 - 0.0953 \cdot \ln x$$

in the useful range of depths

$$5.5 \text{ m} \geq x \geq 0.2 \text{ m}$$

which was found by fitting a straight line on derived data in a logarithmic graph.

In order to be able to estimate the effects on the calculated thermal performance, the R–N transmission function was replaced in our salt gradient solar pond numerical model by the derived polynomial approximation. Typical results are shown in Fig. 4 for a pond operating in a midlatitude country with a storage zone of 0.8 m, upper mixing zone of 0.1 m, underground water flow of 10° C, at 6 m under the bottom of the pond with bottom absorptivity $\alpha_b = 0.85$, for a gradient zone thicknesses of 0.5, 1.0, and 1.5 m deep.

As can be seen, heat collection efficiency is appreciably improved for the three nonconvecting zone thicknesses over a wide range of operating temperatures.

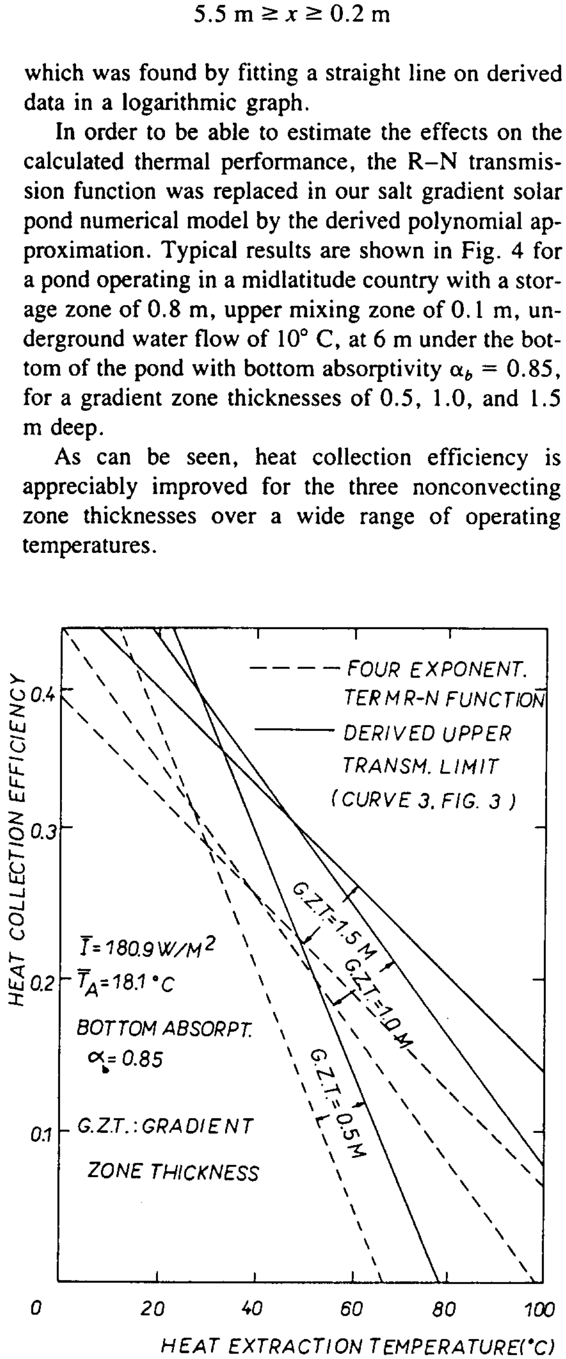

Fig. 4. Comparative steady-state, thermal performance results, according to derived and 4 exponential term R–N function for three gradient zone thicknesses. Daily average (yearly) solar insolation level $\bar{I}$ = 180.9 W/M², daily average temperature $\bar{T}_A$ = 18.1° C (38°N Lat., Athens, Greece).

5. CONCLUSIONS

It has been found that the R–N four exponential term transmission function does not represent the upper radiation transmission limit for the direct beam as it is based on earlier performed calculation. By numerical intergration calculations and by division of the solar spectrum in 19 nonequally spaced bands, it was found that an upper theoretical transmission limit for the direct beam could be set if the pond water could be kept as clear as distilled water. This does not necessarily mean that waters of operational ponds open to the environment may be kept easily, absolutely free of organic substances, debris, or algae, which are responsible for clarity degradation, like carefully filtered oceanic water, but it demonstrates the improvement in transmission and efficiency that may be achieved with a good pond water management. The improvement on calculated transmission now found is due mainly to the selection of the more favorable AM = 1 solar spectrum and to the better mathematical accuracy offered by the employed calculations.

There are also important implications in the calculated thermal performance of salt gradient solar ponds. Introduction of the derived function in thermal performance models leads to heat extraction efficiencies, appreciably higher than those calculated using the four-term transmission function.

It is also concluded that for a rough estimation of thermal performance it would be sensible to introduce a water quality dimensionless factor, in terms of the upper standard distilled water transmission limit for the direct radiation. This factor, describing the practical water transmission limits within which the pond could be operated economically, could be set for practically very pure pond water, at such value (0.7–0.75), as to give transmittances near the R–N transmission function[32]. Even though distilled-water data have been used in these calculations, some indications in the literature of measurements in clear natural water (Crater Lake, USA)[33], appear even more favorable. The phenomenon may be possibly attributed to the presence of an appreciable diffuse component that is penetrating the natural water body deeply.

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