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Transparent Properties of Pure and Impure Salty Waters for a Solar Pond Body*

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Abstract

In this study, the spectral transmittance of pure and impure sodium chloride water solutions, which is important for the thermal calculation of a solar pond, is measured for specimens of thicknesses of 1~100 mm by means of an autorecording spectro-radiometer inside an air-conditioned room.

Then, based on the spectral transmittance obtained here, the total transmittance of these pure and impure salty waters up to 3.2 m deep is calculated as a ratio of the total radiation energy over all wavelengths arrived at any depth from the water surface of the solar pond to solar radiation incident upon the water surface with various air masses. According to the five-partition method extended from Nielsens' four-partition method of wavelength, the absorption coefficient is calculated for each wavelength band.

Finally, these transparent properties obtained for the pure and impure salty waters, i. e., the spectral and total transmittances, and the absorption coefficient for each wavelength band, are compiled as basic data for the use of solar energy by a solar pond.

1. Introduction

The authors have measured the spectral transmittance and calculated the total transmittance of pure and salty waters, and the method and accuracy of these measurements and some parts of the results of the experiments and the calculations have already been reported[1~4].

The main purpose of this study is firstly to make experimentally clear the spectral transmittance of the water solutions of pure and impure salts in various high concentrations, which are important for the thermal analysis of a solar pond. Next, based on the spectral transmittance obtained here, the total transmittance of the pure and impure salty waters for all wavelengths of solar radiation is calculated as a ratio of the radiation energy which arrives at any depth from the water surface of the solar pond to the radiation incident upon the water surface with various air masses. Lastly, these transmission properties for pure and impure salty waters are compiled as the basic data for thermal calculation of a solar pond.

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2. Measurements of Spectral Transmittance

For measurement of the spectral transmittance, the double beam method was adopted for the wavelength range 0.36~25 μm using an autorecording spectroradiometer (JASCO SR-3) as shown in Fig. 1. A tungsten lamp was used as the light source for the visible region (0.36~0.8 μm) and for the near-infrared region (0.75~1.2 μm), and a siliconite heat source was used for the infrared region (1~25 μm). Two couples composed of a flint-glass prism and two sorts of photomultiplier were used for the former two ranges, and a couple composed of a

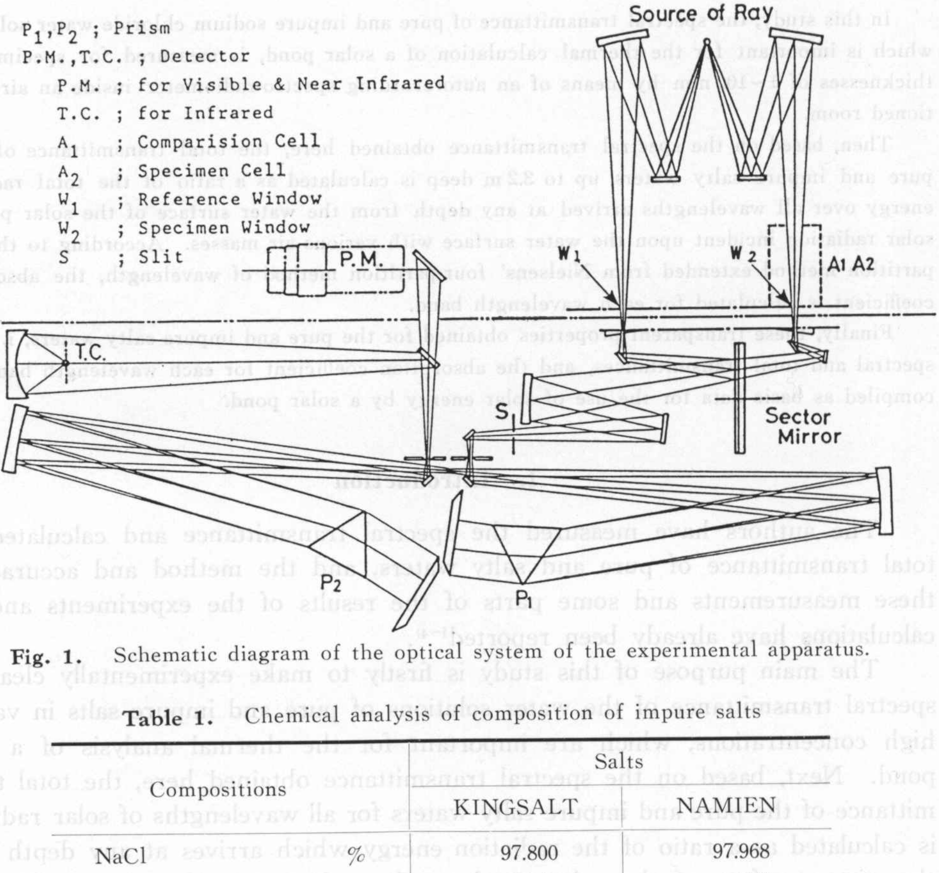


Fig. 1. Schematic diagram of the optical system of the experimental apparatus.

Table 1. Chemical analysis of composition of impure salts

Compositions		Salts	
		KINGSALT	NAMIEN
NaCl	%	97.800	97.968
Water	%	1.618	1.576
Ca	%	0.039	0.060
Mg	%	0.051	0.046
K	%	0.090	0.104
Sulfate radical	%	0.021	0.081
Others	%	0.381	0.165
Total		100.000	100.000

Manufacturing process : ion-exchange resin method
Materials : sea water

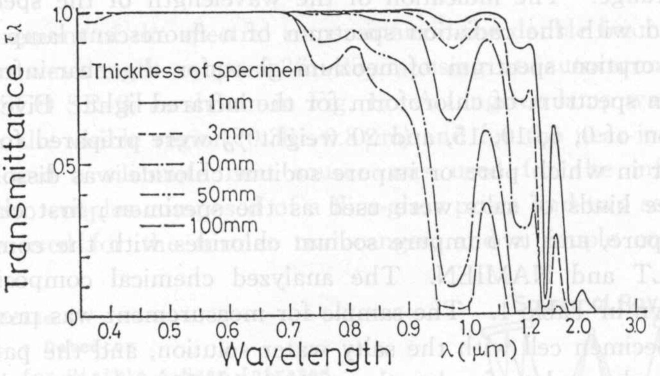
KBr prism and a vacuumed thermocouple detector (with KBr glass) was used for the last range. The indication of the wavelength of the spectro-radiometer was calibrated with the radiation spectrum of a fluorescent lamp for the visible light, the absorption spectrum of neozium glass for the near-infrared light, and the absorption spectrum of chloroform for the infrared light. Five concentrations of the solution of 0, 5, 10, 15, and 20 weight % were prepared for the specimen of salty water in which pure or impure sodium chloride was dissolved in distilled water. Three kinds of salts were used as the specimen ; first class NaCl more than 99.5% pure, and two impure sodium chlorides with the commercial names of KINGSALT and NAMIEN. The analyzed chemical compositions of these salts are shown in Table 1. The sample for measurement was prepared by filling a sectional specimen cell with the salty water solution, and the pathlength of the specimen was changed to five lengths of 1, 3, 10, 50 and 100 mm thick by using a spacer.

The procedure of measurement by means of the autorecording spectro-radiometer is as follows : firstly for the measurement of a standard value, the comparison cell is placed in front of the specimen window W_2 of the spectro-radiometer, and the intensity of the ray passed through the comparison cell is recorded as a spectral value of around 97% of the full scale of the ordinate on the chart. Next, the specimen cell is used for the measurement of the sample value instead of the comparison cell, and then the same operation as above is repeated so that, in general, a smaller value for the specimen cell is recorded on the same chart. Finally, the spectral transmittance can be produced as the ratio of the spectral value for the specimen cell to that for the comparison cell by comparing the heights of the two curves recorded on the chart at each wavelength. Throughout the operation, window W_1 for the reference beam of the spectro-radiometer is always open without any materials in front of it. All the measurements were carried out inside an air-conditioned room in which the temperature was kept at 21±1°C and the relative humidity was under 50%.

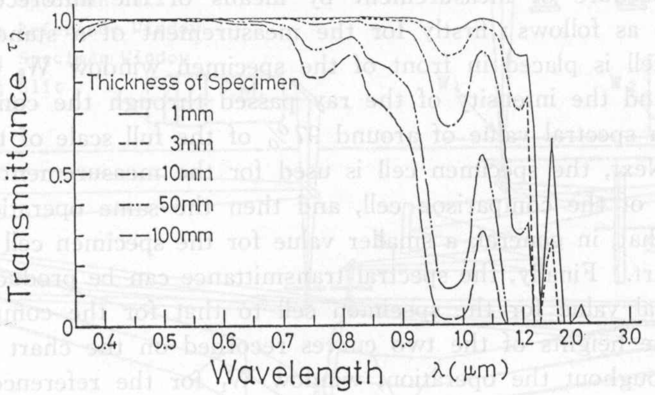
3. Results and Discussion

Figures 2 (a), (b) and (c) show the measured results of the spectral transmittances of NaCl, KINGSALT and NAMIEN water solutions of 20% concentration and 1～100 mm specimen thickness. The wavelength dependence of the spectral transmittance for the NaCl water solution of a specimen thickness smaller than 3 mm resembles that of the pure water and the value of the spectral transmittance is almost 100% over the visible wavelength range as shown in Fig. 2 (a). A little absorption appears at the range near 0.76 μm and the absorption increases somewhat for the range of 0.8～0.9 μm except for a slight transmission near 0.82 μm. Moreover, there is a high absorption band at the range of 0.95～1.0 μm and a small peak of transmission near 1.08 μm, and when the pathlength of the specimen is more than 3 mm the transmittance becomes zero for a ray of wavelength more than 2 μm due to the severe absorption. The spectral transmittances

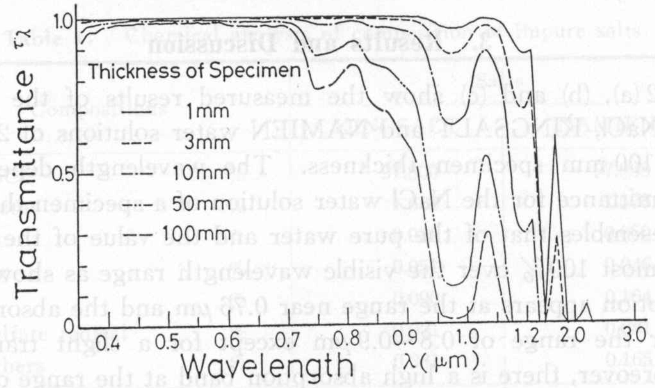
(a) NaCl Solution 20%



(b) KINGSALT Solution 20%

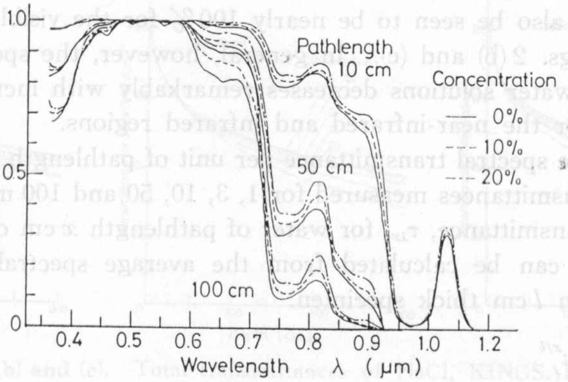


(c) NAMIEN Solution 20%

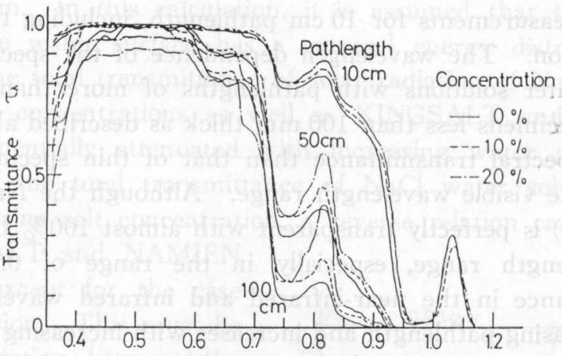


Figs. 2 (a), (b) and (c). Spectral transmittance of NaCl, KINGSALT and NAMIEN water solutions for specimen thicknesses of 1～100 mm.

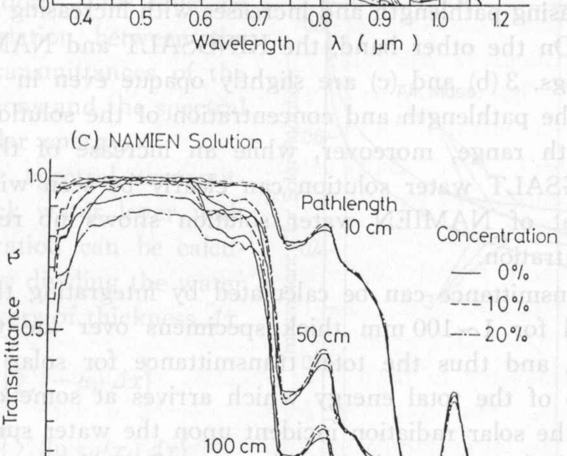
(a) NaCl Solution



(b) KINGSALT Solution



(c) NAMIEN Solution



Figs. 3 (a), (b) and (c). Spectral transmittance of NaCl, KINGSALT and NAMIEN water solutions for pathlengths of 10~100 cm.

for KINGSALT and NAMIEN water solutions of 20% concentration and thinner than 3 mm can also be seen to be nearly 100% for the visible wavelength range as shown in Figs. 2 (b) and (c). In general, however, the spectral transmittance for these salty water solutions decreases remarkably with increasing thickness of the specimen for the near-infrared and infrared regions.

The average spectral transmittance per unit of pathlength was calculated from the spectral transmittances measured for 1, 3, 10, 50 and 100 mm thick specimens. The spectral transmittance, $\tau_{\lambda x}$, for water of pathlength x cm deeper than a 10 cm thick specimen can be calculated from the average spectral transmittance, $\tau_{\lambda l}$, measured for an l cm thick specimen.

$$\tau_{\lambda x} = \tau_{\lambda l}{}^{x/l} \tag{1}$$

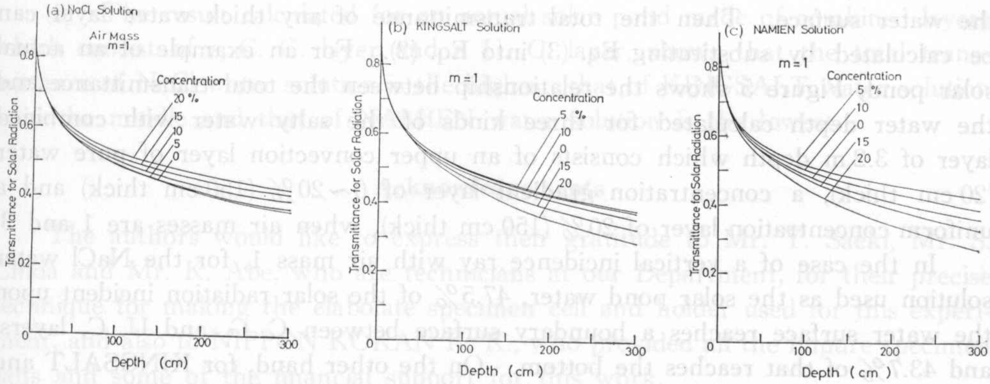
Figures 3(a), (b) and (c) show the spectral transmittances of NaCl, KINGSALT and NAMIEN water solutions of 10 and 20% salt concentration and pathlengths of 50 and 100 cm calculated from the average spectral transmittance according to Eq. (1) and the measurements for 10 cm pathlength, including that of pure water of 0% concentration. The wavelength dependence of the spectral transmittance for three salty water solutions with pathlengths of more than 10 cm is similar to that of thin specimens less than 100 mm thick as described above, and a larger decrease of the spectral transmittance than that of thin specimen can evidently be seen outside the visible wavelength range. Although the NaCl water solution shown in Fig. 3 (a) is perfectly transparent with almost 100% transmittance over the visible wavelength range, especially in the range of 0.45~0.58 μm, the spectral transmittance in the near-infrared and infrared wavelength ranges decreases with increasing pathlength and increases with increasing salt concentration of the solution. On the other hand, the KINGSALT and NAMIEN water solutions shown in Figs. 3 (b) and (c) are slightly opaque even in the visible region when increasing the pathlength and concentration of the solutions. In the near-infrared wavelength range, moreover, while an increase of the spectral transmittance of KINGSALT water solution can clearly be seen with increasing salt concentration, that of NAMIEN water solution shows no relation to changes in the salt concentration.

The total transmittance can be calculated by integrating the spectral transmittance averaged for 1~100 mm thick specimens over the wavelength of an incident radiation, and thus the total transmittance for solar radiation can be defined as a ratio of the total energy which arrives at some distance from the water surface to the solar radiation incident upon the water surface. Therefore, the equation to calculate the total transmittance τ from the spectral transmittance τ_λ is

$$\tau = \int_0^\infty \tau_\lambda I_\lambda \, d\lambda \Big/ \int_0^\infty I_\lambda \, d\lambda \tag{2}$$

where, I_λ is the spectral distribution of incident energy.

Figures 4 (a), (b) and (c) show the results calculated for the total transmit-



Figs. 4 (a), (b) and (c). Total transmittances of NaCl, KINGSALT and NAMIEN water solutions for solar radiation up to 3 m depth.

tances of NaCl, KINGSALT and NAMIEN water solutions for solar radiation up to a depth of 3 m. In this calculation, it is assumed that the solar radiation incident upon the water surface has a spectral energy distribution of an air mass $m=1$[5]. The total transmittance of solar radiation of NaCl water solutions with various salt concentrations as well as KINGSALT and NAMIEN water solutions is exponentially attenuated with increasing water depth. While the absolute value of the total transmittance of NaCl water solution increases in order with increasing salt concentration, a reverse relation can be observed for those of KINGSALT and NAMIEN water solutions except for the case of 0% concentration. This must be caused by the relation between the spectra of the transmittances of the three water solutions and the spectral distribution of solar energy.

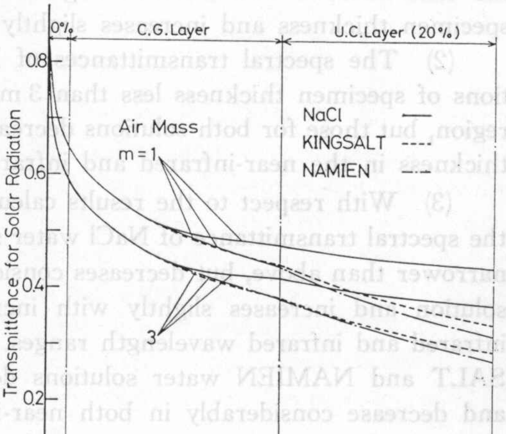


Fig. 5. Relationship between the total transmittance and water depth for the combined layers with a total depth of 3.2 m.

The average spectral transmittance of any thick water layer with any salt concentration can be calculated by Eq. (3) by dividing the water layer into thin layers of thickness Δx.

$$\tau_\lambda = \exp\left\{\sum(-\mu_i)\,\Delta x\right\}$$
$$= \exp\left\{\sum(\ln \tau_{\lambda i}/x_i)\,\Delta x\right\} \qquad (3)$$

where, $\tau_{\lambda i}$ and μ_i are the spectral transmittance and absorption coefficient respectively of the i-th layer of each thin layer at depth x_i from the water surface. Then the total transmittance of any thick water layer can be calculated by substituting Eq. (3) into Eq. (2). For an example of an actual solar pond, Figure 5 shows the relationship between the total transmittance and the water depth calculated for three kinds of the salty water with combined layer of 3.2 m depth which consists of an upper convection layer of pure water (20 cm thick), a concentration gradient layer of 0～20% (150 cm thick) and a uniform concentration layer of 20% (150 cm thick), when air masses are 1 and 3.

In the case of a vertical incidence ray with air mass 1, for the NaCl water solution used as the solar pond water, 47.5% of the solar radiation incident upon the water surface reaches a boundary surface between C. G. and U. C. layers, and 43.7% of that reaches the bottom. On the other hand, for KINGSALT and NAMIEN water solutions, 44.3% and 43.8% of the incident radiation reach the boundary, and 33.8% and 31.7% of that reach the bottom respectively. Comparing the total transmittance for the impure salt water solutions with that for the pure salt water solution, the values for KINGSALT and NAMIEN are 6.7% and 7.8% less than those for NaCl at the boundary, and then the values for the former are 22.7% and 27.5% respectively less than those for the latter at the bottom, because of impurities contained within them.

4. Conclusions

(1) The spectral transmittance of NaCl water solution of 1～100 mm specimen thickness is almost 100% over all visible wavelength ranges, but that for the near-infrared and infrared regions decreases considerably with increasing specimen thickness and increases slightly with increasing salt concentration.

(2) The spectral transmittances of KINGSALT and NAMIEN water solutions of specimen thickness less than 3 mm are also nearly 100% over the visible region, but those for both solutions decrease considerably with increasing specimen thickness in the near-infrared and infrared regions.

(3) With respect to the results calculated for pathlengths geater than 10 cm, the spectral transmittance of NaCl water solution is almost 100% at visible regions narrower than above, but decreases considerably with increasing pathlength of the solution and increases slightly with increasing salt concentration in the near-infrared and infrared wavelength ranges. The spectral transmittances of KINGSALT and NAMIEN water solutions decrease slightly over the visible region, and decrease considerably in both near-infrared and infrared regions when the pathlength increases. However, the former decreases with increasing salt concentration, while the latter increases with changing salt concentration.

(4) The total transmittance of solar radiation of a NaCl water solution with various salt concentrations and of KINGSALT and NAMIEN water solutions is exponentially attenuated with increasing water depth. While the absolute value of the total transmittance of NaCl water solution increases in order with increasing salt concentration, the reverse relation can be observed for those of KINGSALT and NAMIEN water solutions except in the case of 0% concentration.

(5) The result calculated for an actual solar pond made of combined layers which consist of a C. G. layer and a U. C. layer, shows that the total transmittance of NaCl water solution is the highest, that of KINGSALT water solution is in the middle and that of NAMIEN water solution is the lowest.

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