Int. J. Heat Mass Transfer. Vol. 21, pp. 1379–1384
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0017-9310/78/1101-1379 $02.00/0

COMPARISON OF PREDICTIONS WITH MEASUREMENTS FOR RADIATIVE TRANSFER IN AN ALGAL SUSPENSION

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(*Received 5 December* 1977 *and in revised form* 17 *March* 1978)

Abstract—The radiation field within a scattering–absorbing suspension of unicellular algae has been determined experimentally and theoretically. A submerged fiber optic probe was used to measure the angular variation of the radiation intensity at different depths in a diffusely irradiated culture of *Chlorella pyrenoidosa*. The measurements were also used to determine the variation of the radiative flux with depth in the culture. The measured directional distributions agree well with predictions of the radiation field based on the method of discrete ordinates. Good agreement with the data for the radiative flux is also obtained from predictions based on a six-flux model as well as on the method of discrete ordinates. However, predictions based on the simpler two-flux and Beer's law models deviate significantly from the measured results.

NOMENCLATURE

b,	distance from the front to the rear surface of the culture [m];
F_λ,	monochromatic radiant flux, [W/m^2 μm];
I_λ,	monochromatic radiant intensity [W/m^2 sr μm];
n,	index of refraction;
p_λ,	monochromatic phase function;
x,	distance from the front surface of the culture [m].

Greek symbols

β_λ,	monochromatic extinction coefficient [1/cm];
θ,	declination angle [rad];
μ,	$\cos\theta$;
ρ,	reflectivity;
τ_λ,	monochromatic optical depth;
ϕ,	azimuthal angle [rad];
Ω,	solid angle [sr];
ω_λ,	monochromatic scattering albedo.

Subscripts

b,	rear surface of the culture;
i,	incident radiation;
p,	in the Plexiglass;
pa,	Plexiglass–air interface;
w,	in the water;
wp,	water–Plexiglass interface;
$+$,	forward direction;
$-$,	backward direction.

INTRODUCTION

Existing and anticipated applications, as well as concern for the natural environment, have stimulated interest in predicting solar radiation transfer in water bodies. For example, ponding systems are being used for the dissipation of power-plant waste heat, the treatment of wastewater, and the intensive culture of edible aquatic organisms. They are also being considered for use in the collection of solar energy. In such applications knowledge of the local radiation field is essential to predicting both the thermal structure and the growth of photosynthetic organisms within the water.

Solutions for the radiation field in a water body have been obtained at various levels of complexity, depending upon the degree to which multiple scattering effects are considered. The simplest solutions involve use of a Beer's law, or single-flux approximation, in which scattering effects are neglected [1–4]. Scattering effects may be treated through the use of multi-flux models [3, 5–7], as well through the detailed method of discrete ordinates [4, 8]. The relative merits of using the one, two and six-flux approximations, as well as the method of discrete ordinates, for the water environment have recently been considered [9]. Moreover, the potential for using such methods to accurately predict the radiation field in a water body is being enhanced by the development of a reliable data base for the required radiative properties [10–12]. In particular, measurements are being made for the absorption and scattering coefficients, as well as the scattering phase function, of aqueous media which contain various suspended solids.

Despite the considerable interest in predicting radiative transfer within bodies of water, little has been done to test the validity of existing solution methods. The present study was undertaken to remedy this situation by comparing measurements of the radiation field in a large algal culture with predictions based on representative methods of solving the equation of radiative transfer. In addition to being an integral part of the natural aquatic environment, algae may be grown intensively for use as a high protein food supplement and for the enhancement of wastewater treatment. Moreover, since their inherent radiative properties have been accurately determined, they are well suited for use in the comparisons of this study.

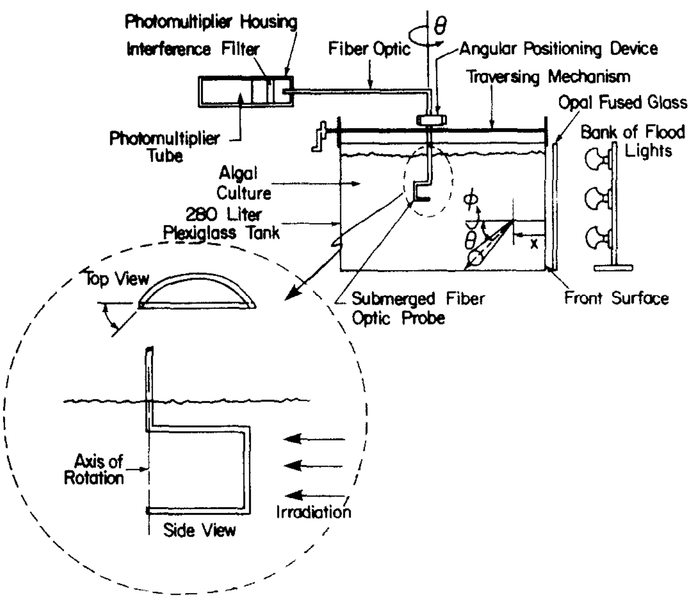

FIG. 1. Schematic of the test cell and the optical system.

EXPERIMENTAL METHODS

A schematic of the system used for the radiation measurements is shown in Fig. 1. A 300 l Plexiglass tank (0.64 m deep and 0.60 by 0.78 m on the sides) was used as a container for the algal culture. The container was filled with a nutrient solution [11] and seeded with a dense 1 l culture of the algal species *Chlorella pyrenoidosa* (Strain 71105). After seeding, the culture was allowed to grow at room temperature under a light source comprised of seven 75 W flood lights. During periods of growth and subsequent data acquisition, the culture was slowly stirred in order to prevent bleaching or settling of the algal cells. Serial dilution and subsequent plating on agar revealed that bacterial cells comprised less than 7% of the particle population and that the culture was free of clumped algal cells. The algal cell size distribution and population density were obtained using a Coulter counter (Model F) with a 70 μm aperture. *C. pyrenoidosa* cells are nearly spherical and the average cell diameter for the conditions of this study was approximately 3 μm. The population density was approximately 1.5×10^7 cells/cm^3, and the extinction coefficient was approximately 2 (1/cm). The cultures were considerably more opaque than those associated with the natural aquatic environment and provide an upper limit to the opacity associated with aqueous suspensions.

During data acquisition, the culture was irradiated in the horizontal direction from one side of the tank (Fig. 1). Radiation originating from a bank of ten 75 W flood lights was transferred through an opal fused glass plate to the tank in order to achieve nearly uniform, diffuse irradiation of the culture. With this arrangement, radiation measurements could be taken as a function of position in the culture simply by traversing a submerged radiation detector.

Due to the large tank size and the large opacity of the culture, it is reasonable to assume one-dimensional transfer in a plane-parallel system. Two-dimensional effects are associated with reflections at the tank boundaries and the air-water interface, but the effects are confined to regions of the culture which are close to the boundaries. A beam of radiation normally incident to and reflected from the air–water interface, for example, would be attenuated by a factor of 0.10 within a distance of 2 cm from the interface. The validity of the assumption was verified experimentally by submerging the radiation detector 0.3 m below the air-water interface. At a distance of 0.15 m from the irradiated surface of the tank, the detector was traversed along the plane of the irradiation, and the standard deviation of the measurements was found to be less than 2%.

Monochromatic radiation measurements were made by submerging a fiber optic probe in the culture. The probe was constructed of stainless steel tubing (1.9 mm O.D., 1.6 mm I.D.), in which a 1 mm monofilament plastic fiber was inserted [11]. The probe was capped with a barrel guide having a 0.33 mm aperture which was covered with a plastic window and separated from the fiber tip by a distance of 12 mm. The half angle of view was determined to be 0.024 rad (1.4°) by measuring the output of the probe as it was rotated about an axis perpendicular to a beam of white collimated light.

At any position in the culture the probe tip could be rotated in the θ direction in order to determine the directional distribution of the radiation field. The curved shape of the probe (Insert, Fig. 1) was chosen in order to determine if shading effects would cause significant error during the course of such measurements. That is, shading of the probe tip by the housing when radiation measurements are made for the backward (negative x) direction could influence the accuracy of the measurements. If such an effect were significant the asymmetry of the probe around its direction of view would result in an asymmetrical radiation pattern. However, because no such asymmetries were recorded and radiation propagation in the backward direction is small, it was concluded that the effect could be neglected.

The probe was supported above the tank by a traversing mechanism which permitted probe travel in each of the three rectangular coordinates, as well as rotation about a vertical axis. The radiant output of the fiber was rendered monochromatic by passing it through a 513 nm interference filter (Special Optics 9-2103-5145) which had a bandwidth of 8 nm. The monochromatic radiation was then measured with a photomultiplier tube (EMI 9558 Q). Signal processing was effected by a digital multimeter (Keithley Model 160), whose analog output was averaged over 10 s using a Vidar (Model 260) voltage to frequency converter and a Hewlett–Packard (Model 5216 A) frequency counter. The averaged signal was then recorded by a paper tape printer (United Systems, Model 620). Note that the output of the photomultiplier tube, P, is proportional to the average intensity, $\bar{I}_\lambda$, of the radiation intercepted by the exposed end of the optical fiber. The proportionality may be expressed as

$$P = \alpha \int_{A_f} \int_{\Omega_p} I_\lambda(\Omega) g(\Omega) \mu \mathrm{d}\Omega \mathrm{d}A \tag{1}$$

where α is a proportionality constant related to the sensitivity of the tube, A_f is the exposed area of the fiber, Ω_p is the probe solid angle of view and $g(\Omega)$ is a function accounting for the angular sensitivity of the probe. Since the variation of $I_\lambda(\Omega)$ over the probe field of view is small, it follows that, to a good approximation,

$$P = \left[\alpha \int_{A_f} \int_{\Omega_p} g(\Omega) \mu \mathrm{d}\Omega \mathrm{d}A \right] \bar{I}_\lambda \tag{2}$$

where the term in brackets is a proportionality constant which depends upon the characteristics of the photomultiplier tube and the probe tip design. All measurements of this study are in the form of relative intensities. The experimental error associated with measurements in the forward direction ($\theta \leqslant \pi/2$ rad) is less than 5%, but errors as large as 100% are associated with measurements for the backward direction ($\pi/2 < \theta \leqslant \pi$ rad).

THEORETICAL METHODS

The radiation field within a scattering–absorbing water medium is determined by the equation of transfer, which may be expressed as [13]

$$\begin{aligned} \mu \frac{\mathrm{d}I_\lambda(\tau_\lambda,\mu,\phi)}{\mathrm{d}\tau_\lambda} &= -I_\lambda(\tau_\lambda,\mu,\phi) \\ &+ \frac{\omega_\lambda}{4\pi} \int_0^{2\pi} \int_{-1}^{+1} p_\lambda(\mu',\phi' \rightarrow \mu,\phi) I_\lambda \\ &\qquad (\tau_\lambda,\mu',\phi') \mathrm{d}\mu' \mathrm{d}\phi'. \end{aligned} \tag{3}$$

The dependent variable is the monochromatic intensity, $I_\lambda(\tau_\lambda,\mu,\phi)$, at the optical depth, $\tau_\lambda = \beta_\lambda x$, and in the direction of μ and ϕ. The radiative properties of the medium required for a solution to equation (3) include the extinction coefficient, β_λ, the single-scattering albedo, ω_λ, and the scattering phase function, p_λ. If equation (3) is solved for the intensity as a function of position and direction, the net radiant flux at any position may then be determined from the requirement that

$$F_\lambda(\tau_\lambda) = \int_0^{2\pi} \int_{-1}^{+1} I_\lambda(\tau_\lambda,\mu,\phi) \mu \mathrm{d}\mu \mathrm{d}\phi. \tag{4}$$

By obtaining radiation surveys over μ which agreed to within 2% for values of ϕ which differed by π rad, it was concluded that azimuthal symmetry could be assumed. Accordingly, the integration over ϕ in the above expression may be replaced by 2π.

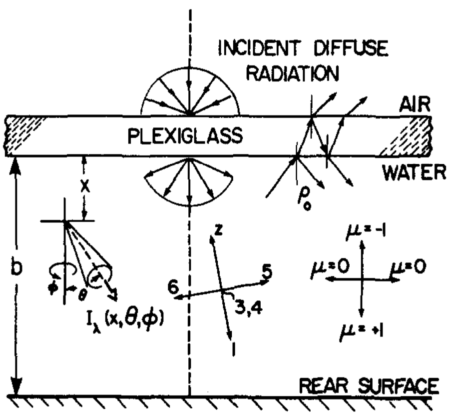

FIG. 2. Coordinate system for the solution methods.

For this study four methods, which represent different levels of sophistication, have been used to solve equation (3), and the relevant geometrical conditions are shown in Fig. 2. The simplest method involves a one-flux, or Beer's law, approximation in which scattering is neglected and all radiation is assumed to propagate as a single collimated beam in the normal ($\theta = 0$, $\mu = 1$) direction. Although the approximation to the actual experimental conditions is highly simplified, it is often made in treating scattering–absorbing media. Its inclusion in this study is therefore intended to demonstrate the magnitude of the error which may arise from its use. The second method involves a two-flux approximation in which the radiation field is divided into downward (positive x) and upward (negative x) components [5]. A major limitation of this method is its inability to account for the anisotropic nature of an interface across which there is an increase in the refractive index. That is, diffuse irradiation is assumed to remain diffuse after transmission, instead of being concentrated within the critical angle associated with refraction. Despite this limitation, two-flux methods are often used to describe scattering-absorbing media, and its inclusion in this study is again intended to identify errors associated with its use.

The third method involves the six-flux approximation suggested by Chu and Churchill[7]. Differential equations are formulated for radiative fluxes propagating in each of six mutually perpendicular directions (Fig. 2), but as for the two-flux formulation, the radiation is assumed to be diffusely distributed for each of the specific directions. For the calculations of this study, μ_1 was chosen to be 0.999. In the last method of solution, the method of discrete ordinates [3, 4, 8], the radiation field is divided into a finite number of directions (ordinates) and a discrete flux is assigned to each direction. With the use of twenty ordinates, a highly detailed determination of the spatial distribution of the radiation field may be obtained. Detailed development of the four methods is provided elsewhere [9, 14].

Solution of equation (3) requires the specification of boundary conditions for the front and back surfaces of the culture tank. At the back surface it is reasonable to assume that the intensity of radiation in the backward direction is zero. Hence irrespective of the solution method this condition may be satisfied by setting the reflectivity of the back surface equal to zero ($\rho_b = 0$). Normalizing the intensity with respect to the value at the water–Plexiglass interface, the front surface condition for the Beer's law approximation is simply specified by setting the dimensionless intensity equal to unity. The corresponding condition for the two-flux approximation is

$$F_+(0) = F_i(0) - \rho_0 F_-(0) \tag{5}$$

where $F_+(0)$ and $F_-(0)$ represent the fluxes in the forward and backward directions at $x = 0$ and $F_i(0)$ is the flux associated with the incident radiation at this point. The quantity ρ_0 represents the reflectivity of the Plexiglass to backward scattered radiation from the water. The rear surface condition is of the form $F_-(b) = 0$. For the six-flux method the front surface conditions are of the form

$$F_1(0) = \mu_1[F_i - \rho_0\mu_2 F_2(0) - \rho_0\mu_5 F_5(0)] \tag{6}$$

and

$$F_6(0) = \mu_6[F_i - \rho_0\mu_2 F_2(0) - \rho_0\mu_5 F_5] \tag{7}$$

and the back surface conditions may be expressed as $F_2(b) = F_5(b) = 0$. Boundary conditions associated with the method of discrete ordinates are developed elsewhere [14].

The reflectivity ρ_0 must account for the multiple reflections which occur due to interactions at both the water-Plexiglass and the Plexiglass-air interfaces. The appropriate expression is of the form [15]

$$\rho_0(\theta_{i,w}) = \rho_{wp}(\theta_{i,w}) + \frac{\rho_{pa}(\theta_{i,p})[1-\rho_{wp}(\theta_{i,w})]^2}{1-\rho_{wp}(\theta_{i,w})\rho_{pa}(\theta_{i,p})} \tag{8}$$

where $\rho_{wp}(\theta_{i,w})$ is the reflectivity of the water-Plexiglass interface to radiation incident at an angle $\theta_{i,w}$ from the water and $\rho_{pa}(\theta_{i,p})$ is the reflectivity of the Plexiglass–air interface to radiation incident at an angle $\theta_{i,p}$ from the Plexiglass. The interface reflectivities may be obtained by using the Fresnel equations [13] with the appropriate refractive indices ($n_p = 1.49$ and $n_w = 1.33$), and the incident angles are related through Snell's law.

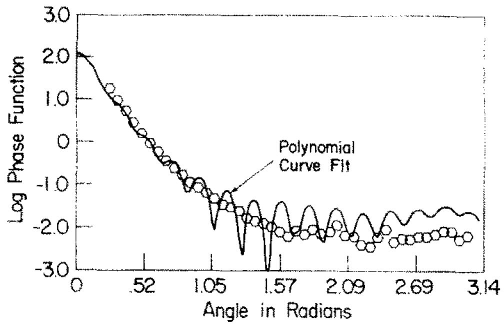

FIG. 3. Phase function data and polynomial curve fit for an algal culture of *Chlorella pyrenoidosa*.

The radiative properties required to solve equation (3) were obtained from measurements performed on a small sample extracted from the culture [11]. For each of the three cultures considered in this study, the value of the single scattering albedo was found to be $\omega_\lambda = 0.91$ at 513 nm, and the value of the extinction coefficient, β_λ, was found to vary from 1.46 to 2.67 cm^{-1}. The phase function, p_λ, was found to be approximately independent of wave-length and culture conditions, and the results used for the calculations of this study are shown in Fig. 3. The data have been fit by a 30 order Legendre polynomial [14] to facilitate the calculations. It is important to note that the phase function is sharply peaked in the forward direction, a condition which has also been observed for numerous samples of natural water [16].

RESULTS

Using the system of Fig. 1 intensity measurements were made as a function of the depth x and angle θ within the culture. At each of several x locations the probe was rotated in a semi-circle, beginning in the

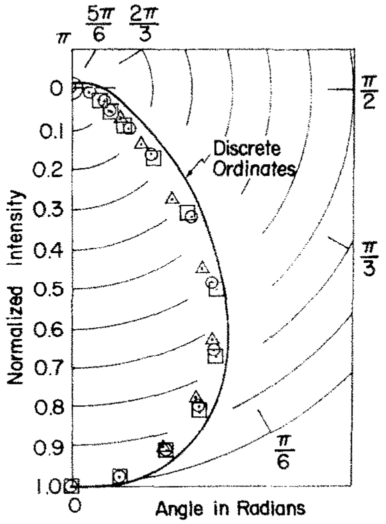

FIG. 4. Angular distribution of the radiation field in a large algal culture: comparison of data with predictions based on the method of discrete ordinates for $\tau_\lambda = 3.7$.

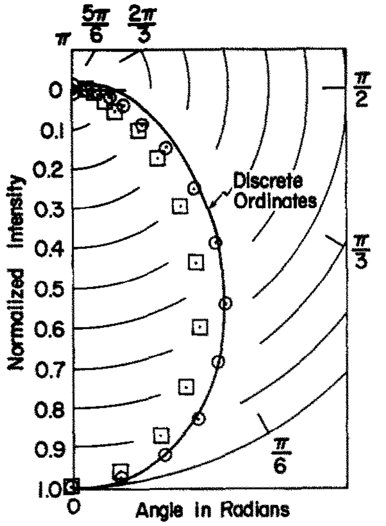

FIG. 5. Angular distribution of the radiation field in a large algal culture: comparison of data with predictions based on the method of discrete ordinates for $\tau_\lambda = 7.7$.

forward direction and proceeding backward, with measurements made every 0.126 rad (7.2°). The flux at a particular x location (or optical depth, $\tau_\lambda = x\beta_\lambda$) was then obtained by substituting the results into equation (4). It should be noted that, since only relative intensity measurements were made, all fluxes were normalized with respect to the surface ($x = 0$) value. Similarly, all theoretical predictions of the flux were normalized with respect to the predicted value at the surface. One shortcoming of this normalization procedure relates to the fact that the shape of the probe precludes measurement of the entire backward flux in the vicinity of the front surface. However, since predictions based on the discrete ordinate method of solution reveal the backward component of the flux to be only 6% of the total at $x = 0$, the error is felt to be acceptable.

Comparisons of experimental and theoretical results for the angular distribution of the radiation intensity are shown in Figs 4 and 5 for two different optical depths. The theoretical results were based on use of the method of discrete ordinates (with 20 ordinates), and the data were obtained from three different cultures. All cultures were characterized by a value of $\omega_\lambda = 0.91$. The cultures represented by the square and circle symbols correspond to $\beta_\lambda = 1.46$ (1/cm), while the culture represented by the triangle corresponds to $\beta_\lambda = 2.67$ (1/cm). Many of the experimental points in the backward direction were omitted from the figures due to a congestion of data near the origin. Although the experimental values were nondimensionalized with respect to the intensity measurement at 0 rad, the theoretical results were normalized with respect to the predicted intensity at 0.117 rad (6.7°). This step was necessitated by the inability to obtain the intensity in the forward direction from the discrete ordinate solution, since it is not a zero of the Legendre polynomials. This inconsistency will not affect the comparison by more than a few per cent.

The agreement between the predicted and measured results of Figs. 4 and 5 is generally good. Differences associated with the forward direction may be attributed to a slight angular misalignment of the probe and to uncertainties in the radiative properties used to effect the solution. Larger differences corresponding to the backward direction may be attributed to the inability to accurately fit a polynomial to the experimental phase function (Fig. 3). Prediction of the total reflectance of a culture using the theoretical methods of this study would be significantly affected by this difficulty.

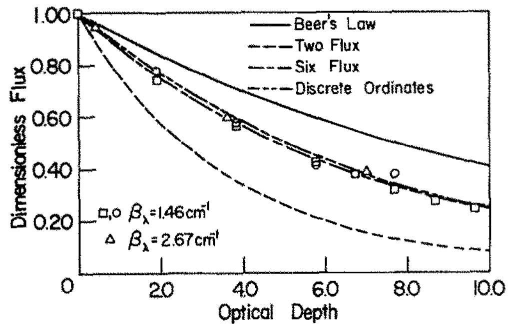

FIG. 6. Comparison of predicted and measured radiative fluxes for a large algal culture.

A comparison of predicted and measured results for the net radiative flux is shown in Fig. 6. It is evident that predictions based on the six-flux and discrete ordinate methods are in excellent agreement with the data, while predictions based on the Beer's law and two-flux models depart significantly from the measured results. The two-flux method consistently underpredicts the data, which is equivalent to this method overpredicting the effects of radiation absorption within the suspension. The discrepancy is due to the inability of the two-flux method to account for the refraction which occurs at $\tau_\lambda = 0$. That is, the method assumes that all radiation propagating into the suspension remains diffuse, when in fact it is concentrated into a cone associated with the critical refraction angle. Conversely, Beer's law over-predicts the flux by assuming a normal collimated beam, thereby failing to treat the actual angular distribution of the radiation field. Note that, due to the large extinction coefficient, $\beta_\lambda \simeq 2$(1/cm), an optical depth of $\tau_\lambda = 10$ is reached at a distance of $x \simeq 5$ cm.

SUMMARY

The purpose of this study has been to develop confidence in using reliable optical property data with accepted methods of solving the equation of transfer to accurately predict radiative transfer within a body of water. This has been done by comparing measured results for the spatial distribution of the radiation field in a diffusely irradiated suspension of unicellular algae with predictions based on four different methods of solving the equation of transfer. The comparisons reveal that, if sufficient attention is given to resolving the angular dependence of the radiation field, as, for example, through use of the six-flux approximation or the method of discrete ordinates, the radiation flux may be accurately predicted. In contrast, highly simplified one-flux and two-flux approximations are inadequate for this purpose.

Acknowledgement—Support of this work by the National Science Foundation under Grant No. ENG 75-17370 is gratefully acknowledged.

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COMPARAISON DE CALCULS ET DE MESURES POR LE TRANSFERT RADIATIF DANS UNE SUSPENSION D'ALGUE

Résumé—Le rayonnement dans une suspension absorbante et diffusante d'algue unicellulaire a été déterminé expérimentalement et théoriquement. Une sonde immergée à fibre optique est utilisée pour mesurer la variation angulaire de l'intensité du rayonnement à différentes profondeurs dans une culture de *chlorella pyrenoidosa* irradiée de façon diffuse. Les mesures permettent aussi la détermination de la variation du flux rayonné avec la profondeur dans la culture. Les distributions directionnelles mesurées s'accordent bien avec les prédictions du champ de rayonnement basées sur la méthode des ordonnées discrètes. Un bon accord avec les mesures pour le flux radiatif est aussi obtenu par une estimation basée sur le modèle à six flux aussi bien que sur la méthode des ordonnées discrètes. Néanmoins, des prédictions faites à partir du modèle plus simple à deux flux et de la loi de Beer s'écartent de façon significative des résultats expérimentaux.

VERGLEICH DES BERECHNETEN UND DES GEMESSENEN STRAHLUNGSÜBERGANGS IN EINER ALGEN-SUSPENSION

Zusammenfassung—In einer streuenden und absorbierenden Suspension von einzelligen Algen wurde das Strahlungsfeld experimentell und theoretisch bestimmt. Es wurde eine faseroptische Tauchsonde verwendet, um die Winkelabhängigkeit der Strahlungsintensität in verschiedenen Tiefen einer diffus bestrahlten Zucht von Chlorella pyrenoidosa zu messen. Die Messungen wurden auch dazu benutzt, die Strahlungsflaßänderung in Abhängigkeit von der Tiefe in der Algenkultur zu bestimmen. Die gemessene Richtungsverteilung stimmt befriedigend mit dem berechneten Strahlungsfeld überein, das mit der Methode der diskreten Ordinaten bestimmt wurde. Gute Übereinstmimmung mit dem Strahlungsfluß wird ebenfalls mit einer Rechnung erreicht, die auf einem "Sechs-Fluß-Modell" sowie auf der Methode der diskreten Ordinaten beruht. Allerdings weichen Rechnungen, die auf dem einfacheren "Zwei-Fluß-Modell" und dem Modell nach dem Beerschen Gesetz beruhen, erheblich von den Maßergebnissen ab.

СРАВНЕНИЕ ТЕОРЕТИЧЕСКИХ И ЭКСПЕРИМЕНТАЛЬНЫХ ДАННЫХ ПО ЛУЧИСТОМУ ПЕРЕНОСУ В ВОДОРОСЛЕВОЙ СУСПЕНЗИИ

Аннотация — В рассеивающе-поглощающей суспензии одноячеечных водорослей экспериментально и теоретически определено поле излучения. Для измерения углового распределения интенсивности излучения на различной глубине в диффузно облучаемой культуре хлореллы пиреноидозы использовался затопленный волоконный оптический датчик. В этих же измерениях определялось изменение потока излучения с глубиной. Измеренные угловые распределения хорошо согласуются с теоретическими расчётами по методу дискретных ординат. Хорошее согласие данных по измерению потока излучения наблюдается также с результатами расчётов по шестипотоковой модели и по методу дискретных ординат. Однако результаты расчётов по более простой двухпотоковой модели и модели, основанной на законе Бэра, существенно отличаются от экспериментальных значений.