and solve equations (1) and (5) by trial and error for W_{1i} and $\overline{W}_{1i}$ where $\overline{W}_{2i} = 1 - \overline{W}_{1i}$. Then W_{2i} is calculated from equation (5) provided subscript 1 is replaced by 2, excluding the molecular weight ratio. The correct T_i is obtained once $W_{1i} + W_{2i} = 1$.

In Fig. 1 exact solution for the heat transfer efficiency, q/q_0, given by Sparrow and Marschall [1] are compared with those obtained from equation (1) for methanol–water mixtures. It may be observed that the maximum deviation between the results is around 10 per cent. Hence, equation (1) is a reasonable solution to the problem and is suggested for practical application. In Fig. 2 it is observed that interfacial suction may increase the condensation efficiency, and in particular for low values of the thermal driving force. This is due to the increase in T_i as compared to the case where suction is absent. In general, however, the improving in condensation due to suction in this case seems to be somewhat less attractive as compared to the effect of suction in the presence of noncondensable gases [4].

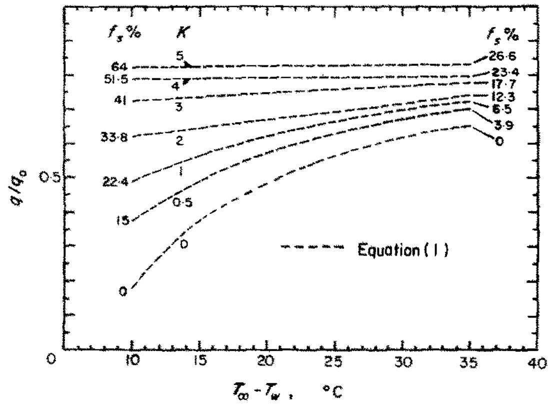

FIG. 2. Effect of interfacial suction on the heat transfer at 370°K and 760 mm Hg.

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HEMISPHERICAL REFLECTIVITY AND TRANSMISSIVITY OF AN ABSORBING, ISOTROPICALLY SCATTERING SLAB WITH A REFLECTING BOUNDARY

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INTRODUCTION

THE REFLECTION and transmission of radiation by a semitransparent medium are affected by the absorption and scattering properties of the medium below the surface, the angular distribution of the incident radiation and the reflection characteristics of the bounding surfaces. A number of investigations have been reported in the literature on the determination of radiative properties of semi-infinite and finite plane-parallel medium respectively for the case of transparent boundaries. The mathematical techniques developed by Chandrasekhar [2] have been used by several investigators [3–7] to investigate the transmission

Table 1. Hemispherical reflectivity of a non-conservative (i.e. $\omega < 1$) slab for isotropic scattering and having a reflecting boundary at $\tau = \tau_0$ and a transparent boundary at $\tau = 0$. Radiation is incident at $\tau = 0$

	Wall reflectivity at τ_0		$\tau_0 = 0{\cdot}1$		$\tau_0 = 0{\cdot}5$		$\tau_0 = 1$		$\tau_0 = 2$		$\tau_0 = 5$		$\tau_0 = 15$		30	
ω	ρ^s	ρ^d	Exact	P_1-App	Exact	P_1-App	Exact	P_1-App	Exact	P_1-App	Exact	P_1-App	Exact	P_1-App	Exact	P_1-App
0·995	0	0	0·0838	0·0693	0·2932	0·2702	0·4412	0·4233	0·5988	0·5890	0·7636	0·7607	0·8438	0·8429	0·8497	0·8489
	0·5	0	0·5213	0·5170	0·5834	0·5739	0·6363	0·6270	0·7040	0·6975	0·7930	0·7904	0·8456	0·8447	0·8497	0·8489
	1·0	0	0·9980	0·9980	0·9901	0·9901	0·9803	0·9803	0·9617	0·9615	0·9151	0·9147	0·8568	0·8560	0·8500	0·8492
	0	1·0	0·9980	0·9980	0·9901	0·9901	0·9803	0·9803	0·9617	0·9615	0·9151	0·9147	0·8568	0·8560	0·8500	0·8492
0·975	0	0	0·0318	0·0673	0·2831	0·2601	0·4206	0·4028	0·5575	0·5476	0·6715	0·6671	0·6949	0·6911	0·6950	0·6912
	0·5	0	0·5170	0·5126	0·5642	0·5541	0·6014	0·5913	0·6440	0·6365	0·6856	0·6812	0·6950	0·6912	0·6950	0·6912
	1·0	0	0·9901	0·9901	0·9519	0·9515	0·9080	0·9070	0·8354	0·8331	0·7274	0·7236	0·6952	0·6914	0·6950	0·6912
	0	1·0	0·9901	0·9901	0·9518	0·9515	0·9078	0·9070	0·8351	0·8331	0·7274	0·7236	0·6952	0·6914	0·6950	0·4912
0·950	0	0	0·0793	0·0648	0·2708	0·2478	0·3964	0·3785	0·5121	0·5014	0·5886	0·5815	0·5967	0·5896	0·5967	0·5896
	0·5	0	0·5117	0·5072	0·5412	0·5303	0·5615	0·5500	0·5813	0·5717	0·5952	0·5879	0·5967	0·5896	0·5967	0·5896
	1·0	0	0·9804	0·9802	0·9074	0·9059	0·8296	0·8260	0·7193	0·7127	0·6106	0·6030	0·5967	0·5896	0·5967	0·5896
	0	1·0	0·9803	0·9802	0·9070	0·9059	0·8290	0·8260	0·7187	0·7127	0·6105	0·6030	0·5967	0·5896	0·5967	0·5896
0·9	0	0	0·0744	0·0599	0·2475	0·2242	0·3527	0·3337	0·4376	0·4233	0·4763	0·4635	0·4780	0·4650		
	0·5	0	0·5014	0·4964	0·4988	0·4854	0·4924	0·4769	0·4837	0·4690	0·4783	0·4652	0·4780	0·4650		
	1·0	0	0·9614	0·9608	0·8275	0·8222	0·7027	0·6914	0·5638	0·5484	0·4819	0·4683	0·4780	0·4650		
	0	1·0	0·9612	0·9608	0·8262	0·8222	0·7009	0·6919	0·5626	0·5484	0·4818	0·4683	0·4780	0·4650		
0·8	0	0	0·0649	0·0501	0·2056	0·1804	0·2806	0·2567	0·3280	0·3059	0·3417	0·3188	0·3419	0·3189		
	0·5	0	0·4814	0·4755	0·4253	0·4054	0·3846	0·3594	0·3527	0·3276	0·3420	0·3190	0·3419	0·3189		
	1·0	0	0·9253	0·9232	0·6964	0·6799	0·5252	0·4976	0·3879	0·3589	0·3425	0·3193	0·3419	0·3189		
	0	1·0	0·9246	0·9232	0·6926	0·6799	0·5208	0·4976	0·3859	0·3589	0·3425	0·3193	0·3419	0·3189		

0·7	0	0	0·0558	0·0406	0·1690	0·1407	0·2221	0·1928	0·2506	0·2203	0·2565	0·2251	0·2566	0·2252
	0·5	0	0·4624	0·4551	0·3638	0·3360	0·3039	0·2688	0·2657	0·2318	0·2566	0·2252	0·2566	0·2252
	1·0	0	0·8914	0·8871	0·5933	0·5633	0·4057	0·3629	0·2850	0·2464	0·2568	0·2252	0·2566	0·2252
	0	1·0	0·8900	0·8871	0·5865	0·5633	0·3992	0·3629	0·2827	0·2464	0·2567	0·2252	0·2566	0·2252
0·6	0	0	0·0470	0·0313	0·1365	0·1046	0·1743	0·1388	0·1919	0·1540	0·1947	0·1559	0·1947	0·1559
	0·5	0	0·4444	0·4353	0·3115	0·2753	0·2408	0·1963	0·2021	0·1604	0·1948	0·1559	0·1947	0·1559
	1·0	0	0·8597	0·8524	0·5099	0·4660	0·3188	0·2631	0·2141	0·1681	0·1948	0·1559	0·1947	0·1559
	0	1·0	0·8574	0·8524	0·5002	0·4660	0·3107	0·2631	0·2118	0·1681	0·1948	0·1559	0·1947	0·1559
0·5	0	0	0·0384	0·0221	0·1077	0·0716	0·1342	0·0924	0·1451	0·1003	0·1465	0·1010	0·1466	0·1010
	0·5	0	0·4272	0·4161	0·2664	0·2217	0·1898	0·1368	0·1526	0·1041	0·1466	0·1010	0·1466	0·1010
	1·0	0	0·8299	0·8190	0·4409	0·3835	0·2521	0·1857	0·1608	0·1084	0·1466	0·1010	0·1466	0·1010
	0	1·0	0·8264	0·8190	0·4284	0·3835	0·2428	0·1857	0·1585	0·1084	0·1466	0·1010	0·1466	0·1010
0·4	0	0	0·0302	0·0132	0·0818	0·0412	0·0999	0·0519	0·1066	0·0555	0·1073	0·0557	0·1073	0·0557
	0·5	0	0·4107	0·3974	0·2271	0·1740	0·1475	0·0868	0·1122	0·0579	0·1073	0·0557	0·1073	0·0557
	1·0	0	0·8018	0·7869	0·3828	0·3126	0·1990	0·1236	0·1183	0·0604	0·1074	0·0557	0·1073	0·0557
	0	1·0	0·7971	0·7869	0·3678	0·3126	0·1888	0·1236	0·1161	0·0604	0·1074	0·0557	0·1073	0·0557
0·3	0	0	0·0223	0·0043	0·0584	0·0132	0·0701	0·0163	0·0741	0·0172	0·0745	0·0173	0·0745	0·0173
	0·5	0	0·3951	0·3793	0·1926	0·1313	0·1117	0·0441	0·0786	0·0188	0·0745	0·0173	0·0745	0·0173
	1·0	0	0·7753	0·7559	0·3332	0·2510	0·1555	0·0723	0·0833	0·0203	0·0745	0·0173	0·0745	0·0173
	0	1·0	0·7693	0·7559	0·3160	0·2510	0·1445	0·0723	0·0812	0·0203	0·0745	0·0173	0·0745	0·0173
0·2	0	0	0·0146		0·0372		0·0439		0·0461		0·0463			
	0·5	0	0·3801	0·3617	0·1619	0·0928	0·0808	0·0070	0·0498		0·0463			
	1·0	0	0·7502	0·7260	0·2902	0·1970	0·1188	0·0290	0·0537		0·0463			
	0	1·0	0·7427	0·7260	0·2709	0·1970	0·1074	0·0290	0·0516		0·0463			
0·1	0	0	0·0072		0·0178		0·0207		0·0216		0·0217			
	0·5	0	0·3656	0·3445	0·1344	0·0579	0·0539		0·0248		0·0217			
	1·0	0	0·7262	0·6972	0·2525	0·1491	0·0874		0·0280		0·0219			
	0	1·0	0·7168	0·6972	0·2312	0·1491	0·0756		0·0261		0·0217			

Table 2. Transmissivity of a non-conservative (i.e. $\omega < 1$) slab for isotropic scattering and having a partially reflecting boundary at $\tau = \tau_0$ and a transparent boundary at $\tau = 0$. Radiation is incident at $\tau = 0$

	Wall reflectivity at τ_0		$\tau_0 = 0{\cdot}1$		$\tau_0 = 0{\cdot}5$		$\tau_0 = 1$		$\tau_0 = 2$		$\tau_0 = 5$		$\tau_0 = 15$		$\tau_0 = 30$	
ω	ρ^s	ρ^d	Exact	P_1-App	Exact	P_1-App	Exact	P_1-App	Exact	P_1-App	Exact	P_1-App	Exact	P_1-App	Exact	P_1-App
0·995	0	0	0·9152	0·9297	0·7018	0·6248	0·5488	0·5668	0·3815	0·3913	0·1892	0·1920	0·0450	0·0453	0·0071	0·0070
	0·5	0	0·4772	0·4815	0·4096	0·4190	0·3504	0·3595	0·2710	0·2773	0·1525	0·1549	0·0388	0·0391	0·0061	0·0061
0·975	0	0	0·9132	0·9277	0·6924	0·7153	0·5313	0·5487	0·3505	0·3594	0·1255	0·1370	0·0087	0·0086	0·0001	0·0001
	0·5	0	0·4777	0·4800	0·4017	0·4110	0·3346	0·3435	0·2417	0·2474	0·1016	0·1028	0·0067	0·0066	0·0001	0·0001
0·95	0	0	0·9108	0·9253	0·6812	0·7036	0·5110	0·5274	0·3175	0·3247	0·0950	0·0948	0·0021	0·0020		
	0·5	0	0·4738	0·4781	0·3923	0·4015	0·3169	0·3253	0·2122	0·2166	0·0670	0·0668	0·0015	0·0014		
0·9	0	0	0·9060	0·9204	0·6599	0·6812	0·4747	0·4885	0·2656	0·2686	0·0534	0·0507	0·0002	0·0002		
	0·5	0	0·4700	0·4744	0·3748	0·3836	0·2868	0·2932	0·1689	0·1703	0·0349	0·0330	0·0002	0·0001		
0·8	0	0	0·8965	0·9107	0·6220	0·6398	0·4162	0·4232	0·1973	0·1917	0·0229	0·0187				
	0·5	0	0·4628	0·4670	0·3450	0·3516	0·2405	0·2427	0·1172	0·1132	0·0137	0·0111				
0·7	0	0	0·8875	0·9012	0·5891	0·6026	0·3712	0·3704	0·1551	0·1425	0·0124	0·0083				
	0·5	0	0·4560	0·4599	0·3202	0·3241	0·2075	0·2050	0·0880	0·0800	0·0070	0·0047				
0·6	0	0	0·8788	0·8919	0·5603	0·5688	0·3355	0·3272	0·1269	0·1091	0·0077	0·0041				
	0·5	0	0·4495	0·4530	0·2993	0·3001	0·1827	0·1758	0·0697	0·0591	0·0042	0·0022				
0·5	0	0	0·8704	0·8828	0·5350	0·5381	0·3067	0·2911	0·1071	0·0855	0·0053	0·0022				
	0·5	0	0·4433	0·4463	0·2816	0·2791	0·1635	0·1526	0·0573	0·0450	0·0028	0·0011				
0·4	0	0	0·8624	0·8738	0·5125	0·5101	0·2830	0·2607	0·0925	0·0681	0·0039	0·0012				
	0·5	0	0·4374	0·4398	0·2663	0·2604	0·1483	0·1338	0·0486	0·0350	0·0020	0·0006				
0·3	0	0	0·8546	0·8650	0·4925	0·4844	0·2631	0·2347	0·0814	0·0551	0·0030	0·0007				
	0·5	0	0·4318	0·4335	0·2529	0·2438	0·1359	0·1183	0·0420	0·0278	0·0016	0·0004				
0·2	0	0	0·8470	0·8564	0·4744	0·4607	0·2463	0·2124	0·0728	0·0451	0·0024	0·0004				
	0·5	0	0·4264	0·4273	0·2412	0·2289	0·1256	0·1054	0·0372	0·0224	0·0012	0·0002				
0·1	0	0	0·8394	0·8480	0·4578	0·4390	0·2317	0·1930	0·0658	0·0373	0·0020	0·0002				
	0·5	0	0·4210	0·4213	0·2307	0·2155	0·1169	0·0944	0·0332	0·0182	0·0010	0·0010				

and reflection of radiation by a semi-transparent medium, and results are reported over a limited range of parameters. In the present analysis an absorbing, isotropically scattering, non-conservative, plane-parallel slab of optical thickness τ_0 is considered. The boundary surface at $\tau = 0$ is transparent while the boundary at $\tau = \tau_0$ is a reflecting one having both specular and diffuse reflectivity components. The hemispherical reflectivity and transmissivity of the slab for isotropic radiation incident on the boundary $\tau = 0$ is determined by using both an exact treatment with the normal-mode expansion technique and a simple approximate analysis with the P_1-approximation. A comprehensive tabulation of the hemispherical reflectivity and transmissivity of the slab obtained by the exact and approximate analysis is presented over a wide range of optical thickness τ_0, single scattering albedo ω and the boundary surface reflectivities ρ^s and ρ^d, and the exact and the approximate results are compared.

ANALYSIS

Consideration is given to an absorbing, isotropically scattering, plane-parallel slab of optical thickness τ_0, irradiated by an isotropic radiation of unit intensity of the boundary $\tau = 0$ which is assumed to be transparent. The boundary surface at $\tau = \tau_0$ is a reflecting one, having a reflectivity ρ which can be expressed as a sum of a specular ρ^s and diffuse ρ^d reflectivity components in the form $\rho = \rho^s + \rho^d$. Re-radiation (i.e. emission) from the medium and the boundary surface $\tau = \tau_0$ is considered negligible. Then the radiation problem satisfies the following equation of radiative transfer and the boundary condition:

$$\mu \frac{\partial I(\tau, \mu)}{\partial \tau} + I(\tau, \mu) = \frac{\omega}{2} \int_{-1}^{1} I(\tau, \mu')\, d\mu', \quad \text{in} \quad -1 \leqslant \mu \leqslant 1, \quad 0 \leqslant \tau \leqslant \tau_0 \qquad (1)$$

$$I(0, \mu) = 1, \ \mu > 0 \qquad (2a)$$

$$I(\tau_0, -\mu) = \rho^s I(\tau_0, \mu) + 2\rho^d \int_0^1 I(\tau_0, \mu')\, \mu'\, d\mu', \ \mu > 0 \qquad (2b)$$

where $I(\tau, \mu)$ is the radiation intensity, τ is the optical variable, μ is the cosine of the angle between the direction of radiation intensity and the positive τ axis, ω is the single scattering albedo and τ_0 is the optical thickness of the slab.

We describe below briefly the exact and approximate methods of solution of the above problem and the determination of the hemispherical reflectivity and transmissivity.

The exact treatment

Using the normal-mode expansion technique the solution of equation (1) can be written in the form [8]

$$I(\tau, \mu) = A(\eta_0)\, \phi(\eta_0, \mu)\, e^{-\tau/\eta_0} + A(-\eta_0)\, \phi(-\eta_0, \mu)\, e^{\tau/\eta_0}, + \int_0^1 A(\eta)\, \phi(\eta, \mu)\, e^{-\tau/\eta}\, d\eta + \int_0^1 A(-\eta)\, \phi(-\eta, \mu)\, e^{\tau/\eta}\, d\eta, \qquad (3)$$

where $\phi(\pm\xi, \mu)$, $\xi = \eta_0$ or $\eta \varepsilon (0, 1)$ are the normal-modes defined in [9], and $A(\pm\xi)$, $\xi = \eta_0$ or η are the unknown expansion coefficients which can be determined by constraining this solution to satisfy the boundary conditions equations (2) and by utilizing the orthogonality property of normal modes and the half-range completeness theorem as described in [8]. Once these expansion coefficients are known, the hemispherical reflectivity R of the slab is determined from the definition

$$R = \left[2\pi \int_0^1 I(0, -\mu)\, \mu\, d\mu\right] / \left[2\pi \int_0^1 \mu\, d\mu\right] \qquad (4)$$

which becomes

$$R = 2\left[A(\eta_0)\, f(-\eta_0) + A(-\eta_0)\, f(\eta_0) + \int_0^1 A(\eta) f(-\eta)\, d\eta + \int_0^1 A(\eta) f(\eta)\, d\eta\right] \qquad (5a)$$

where

$$f(\pm\xi) \equiv \int_0^1 \phi(\pm\xi, \mu)\, \mu\, d\mu, \ \xi \equiv \eta_0 \text{ or } \eta. \qquad (5b)$$

The integrals in equation (5b) can be evaluated analytically. The transmissivity T of the slab is determined from the definition

$$T = \left[2\pi \int_{-1}^{1} I(\tau_0, \mu)\, \mu\, d\mu\right] / \left[2\pi \int_0^1 \mu\, d\mu\right] \qquad (6)$$

which becomes

$$T = 2(1 - \omega)\left[A(\eta_0)\, \eta_0\, e^{-\tau_0/\eta_0} - A(-\eta_0)\, \eta_0\, e^{\tau_0/\eta_0} + \int_0^1 A(\eta)\, \eta\, e^{-\tau_0/\eta}\, d\eta + \int_0^1 A(-\eta)\, \eta\, e^{\tau_0/\eta}\, d\eta\right], \ \omega \neq 1. \qquad (7)$$

The P_1*-approximation*

Using the P_1-approximation (which is equivalent to the Eddington approximation) and the Marshak approximation for the boundary conditions, the radiative transfer problem given by equations (1) and (2) is transformed to the solution of the following simple problem [10]

$$\frac{d^2 G(\tau)}{d\tau^2} - 3(1 - \omega)\, G(\tau) = 0, \text{ in } 0 \leqslant \tau \leqslant \tau_0 \qquad (8a)$$

$$G(\tau) - \frac{2}{3} \frac{dG(\tau)}{d\tau} = 4\pi \quad \text{at } \tau = 0 \qquad (8b)$$

$$(1 - \rho^s - \rho^d)\, G(\tau) + \tfrac{2}{3}(1 + \rho^s + \rho^d) \frac{dG(\tau)}{d} = 0 \quad \text{at } \tau = \tau_0 \qquad (8c)$$

where the function $G(\tau)$ is related to the radiation intensity $I(\tau, \mu)$ and the net radiative heat flux $q(\tau)$ by

$$I(\tau, \mu) = \frac{1}{4\pi}\left[G(\tau) - \mu \frac{dG(\tau)}{d\tau}\right] \qquad (9a)$$

$$q(\tau) = -\frac{1}{3}\frac{dG(\tau)}{d\tau}. \tag{9b}$$

Once the function $G(\tau)$ is determined from the solution of equations (8), the hemispherical reflectivity R and the transmissivity T of the slab are determined according to the foregoing definitions from the following relations.

$$R = \frac{1}{2\pi}\left[G(0) + \frac{2}{3}\frac{dG(0)}{d\tau}\right] \tag{10}$$

$$T = -\frac{1}{3\pi}\frac{dG(\tau_0)}{d\tau}. \tag{11}$$

RESULTS

Tables 1 and 2 show respectively the hemispherical reflectivity and the transmissivity of the slab obtained from the exact analysis and the P_1-approximation for several different values of the optical thickness, single scattering albedo and the boundary surface reflectivities. The absorptivity of the slab can also be determined from the data presented in these tables since the sum of the absorptivity, reflectivity and transmissivity is equal to unity. The exact analysis shows that the reflectivity of the slab is slightly higher with specularly reflecting boundary at $\tau = \tau_0$ than with diffusely reflecting boundary. For optical thicknesses 15 and larger the hemispherical reflectivity is almost equal to that of a semi-infinite medium and transmissivity becomes almost zero. The results with the P_1-approximation, however, do not distinguish whether the reflectivity at the boundary surface $\tau = \tau_0$ is specular or diffuse. The P_1-approximation underestimates the hemispherical reflectivity, and the accuracy of this approximation is not so good for smaller values of ω; for some cases $\omega < 0{\cdot}2$ it has shown negative results which are meaningless. However, for ω close to unity and large optical thicknesses the P_1-approximation gives reasonably good results.

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MONTE CARLO RADIATION SOLUTIONS—EFFECT OF ENERGY PARTITIONING AND NUMBER OF RAYS

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