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TURBULENCE STRUCTURE AND TRANSPORT MECHANISM AT THE FREE SURFACE IN AN OPEN CHANNEL FLOW

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Abstract—The temperature and velocity fields very close to the free surface in an open channel flow were investigated. Instantaneous temperatures at and near the free surface were measured by a thermometer with an i.r. scanner and a resistance thermometer, respectively. Velocity fluctuation was simultaneously measured by laser Doppler velocimetry. The results show that near the free surface, the vertical motions are damped, while the streamwise and spanwise motions are promoted. The surface is renewed by turbulent eddies with a size close to the integral length scale, which are responsible to heat and mass transfer across the free surface. A simple surface renewal model based on these turbulence measurements was presented and the predictions of the liquid-side mass transfer coefficient showed good agreement with previous absorption data of gases into water tunnel, stirred vessel and inclined plate flows.

NOMENCLATURE

D_L,	molecular diffusivity on the liquid-side [m²/s];
f,	frequency [Hz];
k,	$= 2\pi f/\bar{U}$, wavenumber [1/m];
k_L,	liquid-side mass transfer coefficient [m/s];
p,	pressure fluctuation [Pa];
q^2,	$= u^2 + v^2 + w^2$, turbulence kinetic energy [m²/s²];
R,	hydraulic radius [m];
$R_{\theta\theta}$,	space-correlation coefficient of temperature fluctuation;
$S_{ee}(k)$,	normalized power spectrum of e [m];
s,	fractional rate of the surface renewal [1/s];
t,	time [s];
$\bar{T}_{ave}$,	cross-sectional mean temperature [K];
$\bar{U}$,	local mean velocity [m/s];
$\bar{U}_{ave}$,	cross-sectional mean velocity [m/s];
$\bar{U}_{suf}$,	mean velocity in the immediate vicinity of the free surface [m/s];
u,	velocity fluctuation in the streamwise direction [m/s];
u_k,	velocity fluctuation in k-direction [m/s];
u^*,	friction velocity [m/s];
v,	velocity fluctuation in the vertical direction [m/s];
w,	velocity fluctuation in the spanwise direction [m/s];
x,	distance in the streamwise direction [m];
x_i,	distance in i-direction [m];
y,	distance in the vertically upward direction [m];
z,	distance in the spanwise direction [m].

Greek symbols

δ,	flow depth [m];
δ_{ij},	Kronecker delta;
θ,	temperature fluctuation [K];
ν,	kinematic viscosity [m²/s];
ρ,	density of fluid [kg/m³].

Superscript

	root mean square value.

INTRODUCTION

HEAT AND mass transfer across a gas–liquid interface is of practical importance both in geophysics and engineering. Such a process is related with the thermal pollution and re-aeration in river and ocean, and the recycling of heat and mass in the environment. It can be also seen in many industrial processes which include the gas absorption, evaporation equipment and many others. To date, there have been a number of attempts to predict the heat and mass transfer coefficients at the gas–liquid interface theoretically and experimentally.

Experimentally, Fortescue and Pearson [1], Hörner *et al.* [2] and Kataoka and Miyauchi [3] measured mass transfer coefficients for gas absorption in water tunnels; Owens *et al.* [4] in natural streams; Yoshida *et al.* [5] and Prasher and Wills [6] in stirred vessels, and Davies and Warner [7] over an inclined plate. In these previous works, no measurements on turbulence structure were made and attention was restricted to the mass transfer coefficient. Salazar and Marshall [8], Semena and Mel'nichuk [9] and Davies and Lozano [10] measured a few turbulence characteristics by means of hot film velocimetry and optical method. However, these investigations are not complete because of the difficulty of making accurate measurements of turbulence quantities at and near the free surface, and because turbulence structure has not been clarified experimentally.

Theoretically, Hatta [11], Higbie [12] and Dankwerts [13] proposed the classical theories, i.e., the film theory, the penetration theory and the surface renewal theory respectively. In recent years Street [14], Lee and Gill [15], Fortescue and Pearson [1] and others have presented theoretical models for the heat and mass transfer coefficients at the gas–liquid interface. Most of the models are, however, based on hypotheses which have not been verified directly by experiment. In order to develop a more advanced model based on experimental facts, more empirical information on turbulence structure at and near the free surface must be obtained.

The purpose of the present paper is to investigate the turbulence structure and the transfer mechanism at and near the free surface (gas–liquid interface). Simultaneous measurements of velocity and temperature fluctuations were made in open channel flow. A temperature field as a passive scalar was established by evaporation cooling of flowing water that was slightly warmer than room temperature. In the region near the free surface, the temperature gradient was very small, so that the effect of thermal stratification could be neglected.

The measurements include the turbulence intensities, power spectra, joint probability functions and space correlations which were derived from velocity and temperatures fluctuations. Based on these turbulence measurements, a simple surface renewal model was derived and the mechanism of heat and mass transfer across the free surface discussed.

EXPERIMENTAL APPARATUS AND PROCEDURES

Figure 1 illustrates the experimental apparatus and measuring system. The flow was fully developed in an open channel of square cross-section. The inside width and the depth were 0.3 m and 0.06 m respectively, and the length was 6.1 m. Warm water of about 303 K was recirculated through the flume by a pump, its temperature controlled within $\pm$ 0.02 K in a temperature regulating tank.

The measurements were performed at the central part of the flume, at distance 4.1–4.3 m downstream from the entrance. A DISA 55L laser Doppler velocimeter with a DISA 55L02 flow direction adaptor for frequency shift was used for measuring the time-averaged and fluctuating velocity components near the free surface. The laser Doppler velocimeter is most advantageous for the velocity measurements because of the absence of the blocking effect. It worked in the fringe mode with beam intersection angles of 4.4° for the streamwise and vertical velocity fluctuations, and of 22° for the lateral velocity fluctuation. The laser used was a Spectra-Physics 5 mW He–Ne laser (model 120). The Reynolds stress was measured by the Doppler velocimeter following a method analogous to that when using a single slanting hot wire for the same purpose (Durst and Whitelaw [16]).

The time-averaged and fluctuating temperatures at the free surface were measured by using a thermometer with an i.r. scanner with an accuracy greater than 0.05 K (JEOL-Thermoviewer JTG-IB [IBL]). In the flow a miniature TSI 1276-10AW cold film probe operated by a DISA 55M20 constant current temperature bridge was used. Simultaneous voltage outputs from the instruments were directly transmitted to a TEAC DP-4000 data acquisition system in which the signals were digitized and stored on a magnetic tape. The sampling interval and the sample size were 0.01s and about 25,000, respectively. Statistical processing of digitized data recorded on the magnetic tape was made with the FACOM OS IV/F4 computer system.

The flow depth δ was maintained at 0.04 m throughout the flume. The cross-sectional mean velocity $\bar{U}_{ave}$ and temperature $\bar{T}_{ave}$ were equal to 0.07 m/s and

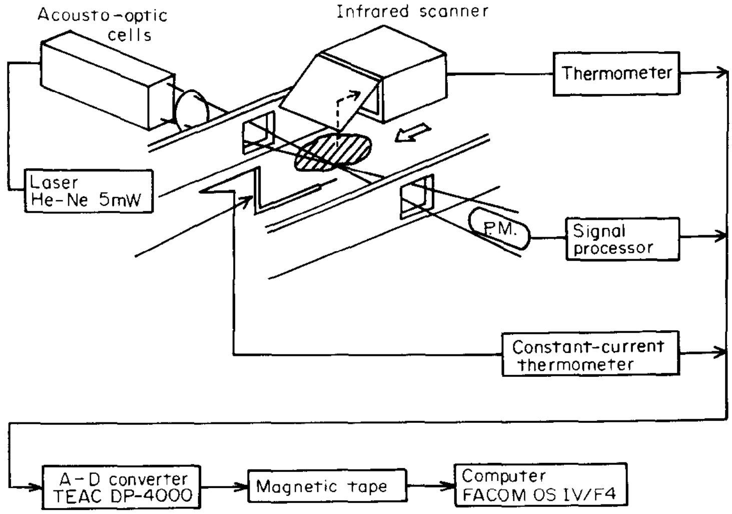

FIG. 1. Experimental apparatus and measuring system.

301.5 K, respectively, so that the Reynolds number $Re\ (=4R\bar{U}_{ave}/\nu)$ was 11,000, where R is the hydraulic radius and ν the kinematic viscosity giving fully developed turbulent flow.

RESULTS AND DISCUSSION

Turbulence intensities

Figure 2 shows the turbulence intensities, i.e. r.m.s. values of the streamwise, vertical and lateral velocity fluctuations, u', v' and w' normalized by the friction velocity u^*. The friction velocity was evaluated by the velocity profile method suggested by Clauser [17]. The intensity of the vertical fluctuation decreases with y/δ, where y is the vertically upward direction from the wall. The decrease of v'/u^* means the damping of the vertical fluctuation due to the gravity and surface tension. Contrarily, the increases of u'/u^* and w'/u^* show the promotion of the streamwise and lateral motions near the free surface. The budget of the turbulence kinetic energy is shown in Fig. 3. In the budget, the energy dissipation was estimated from the power spectral density of the streamwise velocity fluctuation, using the Kolmogoroff hypothesis for the inertial subrange. The convection rate and the work done by the viscous shear stresses could be neglected because the flow was fully developed with high Reynolds number. Approaching the free surface, the shear production rate decreases, and the dissipation becomes balanced by the gain due to the diffusion.

The transport equations for the square values of fluctuating velocity components can be written as:

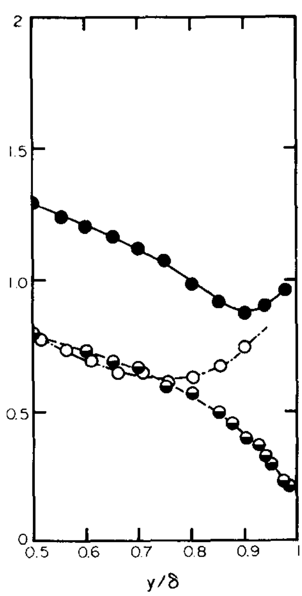

FIG. 2. Distributions of turbulence intensities near the free surface. ●, u'/u^*; ◒, v'/u^*; ○, w'/u^*.

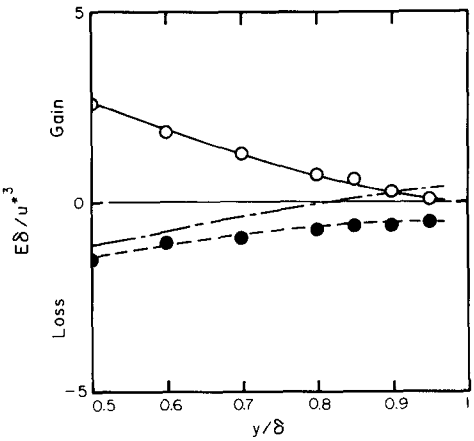

FIG. 3. The budget of the turbulence kinetic energy.

—○—, shear production, $-\overline{uv}\dfrac{\partial \bar{U}}{\partial y}\delta/u^{*3}$;

—●—, viscous dissipation, $-\nu\overline{\left(\dfrac{\partial u_i}{\partial x_j}+\dfrac{\partial u_j}{\partial x_i}\right)\dfrac{\partial u_j}{\partial x_i}}\delta/u^{*3}$;

—·—·—, diffusion, $-\dfrac{\partial}{\partial y}\left[\overline{v\left(\dfrac{p}{\rho}+\dfrac{q^2}{2}\right)}\right]\delta/u^{*3}$.

$$\frac{D\overline{u^2}}{Dt} = -2\overline{uv}\frac{\partial \bar{U}}{\partial y} - 2\nu\overline{\frac{\partial u}{\partial x_k}\frac{\partial u}{\partial x_k}} + 2\overline{\frac{p}{\rho}\frac{\partial u}{\partial x}} - \frac{\partial}{\partial x_k}\left[\overline{u^2u_k} - \nu\frac{\partial\overline{u^2}}{\partial x_k} + 2\delta_{1k}\frac{\overline{up}}{\rho}\right], \quad (1)$$

$$\frac{D\overline{v^2}}{Dt} = -2\nu\overline{\frac{\partial v}{\partial x_k}\frac{\partial v}{\partial x_k}} + 2\overline{\frac{p}{\rho}\frac{\partial v}{\partial y}} - \frac{\partial}{\partial x_k}\left[\overline{v^2u_k} - \nu\frac{\partial\overline{v^2}}{\partial x_k} + 2\delta_{2k}\frac{\overline{vp}}{\rho}\right], \quad (2)$$

$$\frac{D\overline{w^2}}{Dt} = -2\nu\overline{\frac{\partial w}{\partial x_k}\frac{\partial w}{\partial x_k}} + 2\overline{\frac{p}{\rho}\frac{\partial w}{\partial z}} - \frac{\partial}{\partial x_k}\left[\overline{w^2u_k} - \nu\frac{\partial\overline{w^2}}{\partial x_k} + 2\delta_{3k}\frac{\overline{wp}}{\rho}\right], \quad (3)$$

where the repeated indices mean the summation convention. In the region near the free surface the energy of the vertical fluctuation may be redistributed into the energy of the streamwise and lateral fluctuations through the pressure-strain terms in equations (1)–(3). The lateral fluctuation may be more strongly affected than the streamwise one because the shear production is absent in equation (3).

Behaviour of the surface renewal eddy

Figure 4 shows the records of temperature fluctuation, θ, at the various values of y/δ. The θ-signal exhibits intermittent negative spikes which can even be found in the region of $y/\delta \le 0.75$. This suggests that large eddies which have swept away the free surface

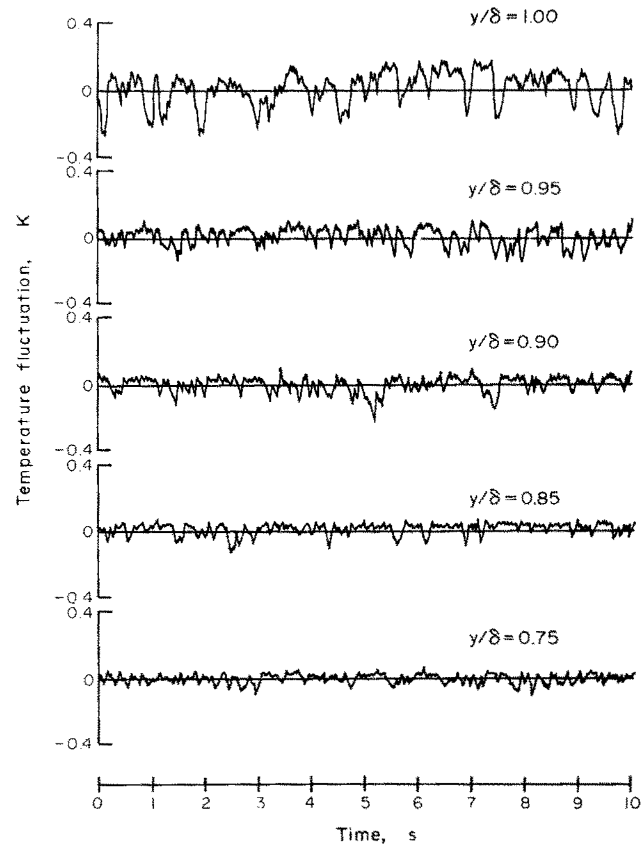

FIG. 4. Records of temperature fluctuation.

come to within deep distance from the free surface. A simultaneous recording of the instantaneous values of θ, v and $v\theta$ at $y/\delta = 0.75$ is shown in Fig. 5. The intermittent negative spikes of θ are accompanied by the negative values of v fluctuation and result in a positive $v\theta$-product as noted by arrows in the figure. This is also confirmed in Fig. 6 by the spread of the outermost area of $v < 0$ and $\theta < 0$ in the joint probability density functions of v and θ. Here, the outermost and innermost rings delineate the probabilities of occurrence of 0.01 and 0.20, respectively. From the joint probability density functions of u and θ shown in Fig. 6, it can be seen that negative spikes of θ are accompanied by the positive values of u. These observations suggest that the surface renewal eddy cooled at the free surface is put back into the bulk flow at a higher speed than the mean velocity.

In order to estimate the frequency of the surface replacement, a threshold level was set with the negative magnitude of 1.6 times the r.m.s. value of θ, as shown on the θ-trace in Fig. 5. This value was selected from the fact that the frequency triggered by a threshold has a plateau in a certain range of threshold level around $1.6\theta'$. The frequency of the appearance f is equal to 0.82 Hz, and the corresponding wavenumber k is 56 (1/m), where k is defined by $k = 2\pi f/\bar{U}_{suf}$ ($\bar{U}_{suf}$; the mean velocity in the immediate vicinity of the free surface). The value of $k = 56$ corresponds to the lower wavenumber in the region of the spectra with slope -1, as shown in Fig. 7. This means that the large and energy-containing eddy renews the free surface.

The scale of the surface renewal eddy can be estimated from the space correlation of the temperature fluctuations. Figure 8 shows the streamwise and lateral correlation coefficients on the free surface, $R_{\theta\theta}(x)$ and $R_{\theta\theta}(z)$, and the vertical correlation coefficient, $R_{\theta\theta}(1 - y/\delta)$, between the point on the free surface and that in the flow. Characteristic length scales of the surface renewal eddy can be determined to be approx. 1.35δ, 1.2δ and 0.5δ in the streamwise, lateral and vertical directions, respectively. The streamwise and lateral length scales determined from the fluctuating temperature field are close to the integral scale obtained by the power spectrum of the streamwise velocity fluctuation.

In order to understand the statistically averaged shape of the surface renewal eddies more clearly, extensive space correlation measurements were taken for the temperature fluctuations between a fixed point on the free surface and an arbitrary point located inside the flow and/or on the free surface. In Fig. 9, iso-correlation contours in x–y, x–z and y–z planes are given, respectively. In the figure, the numbers denote values of the space correlation coefficients. As seen in the correlations in x–y and y–z planes, the contours are strongly elongated horizontally near the free

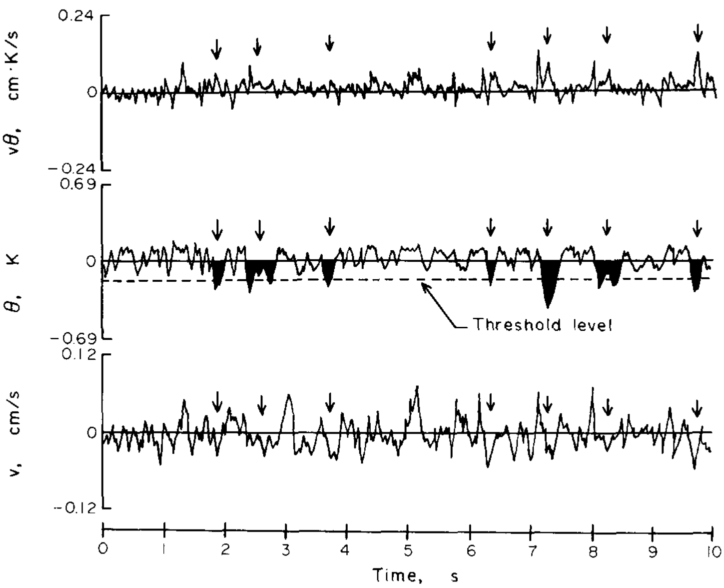

FIG. 5. Simultaneous recording of the instantaneous values of θ, v and $v\theta$ at $y/\delta = 0.75$.

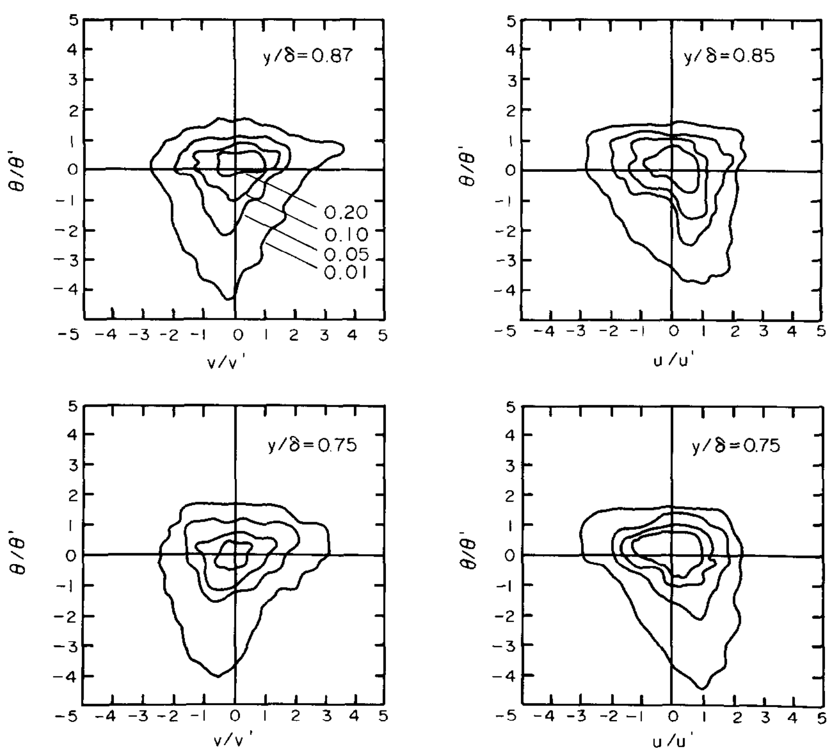

FIG. 6. Distributions of the joint probability density functions of v and θ, and u and θ.

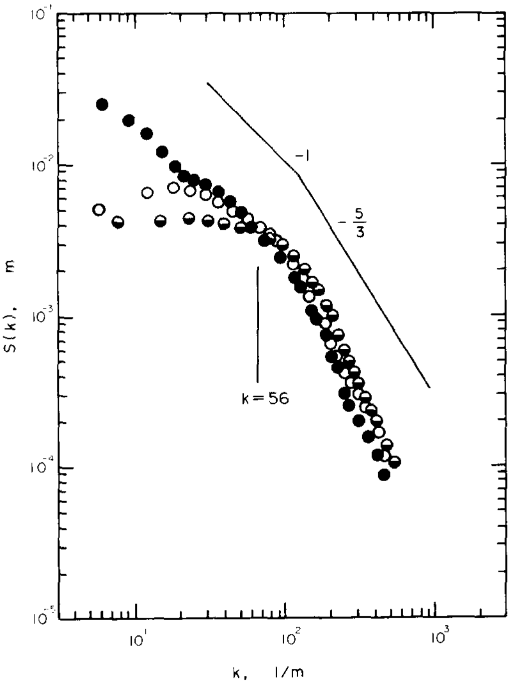

FIG. 7. Normalized wavenumber power spectra of velocity fluctuations near the free surface. ● S_{uu}, power spectrum of streamwise velocity fluctuation; ⊖ S_{vv}, power spectrum of vertical velocity fluctuation; ○ S_{ww}, power spectrum of lateral velocity fluctuation.

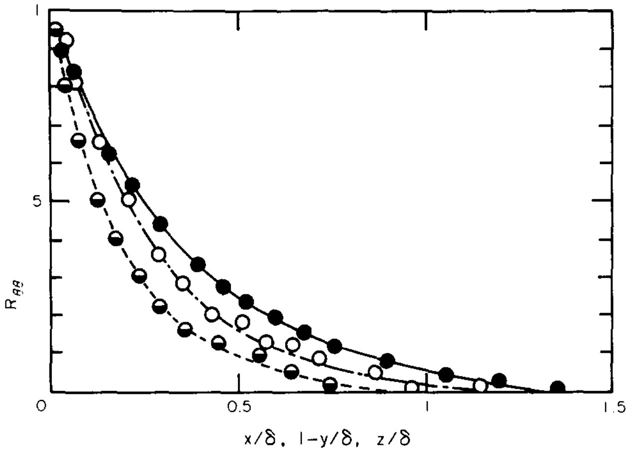

FIG. 8. Distributions of space correlations. ● $R_{\theta\theta}(x)$, streamwise correlation on the free surface; ⊖ $R_{\theta\theta}(1-y/\delta)$, vertical correlation between the point at the free surface and that located inside the flow; ○ $R_{\theta\theta}(z)$, lateral correlation on the free surface.

surface, and on the free surface streamwise spread is larger than the lateral one. As a result, the horizontal extent of the correlation is larger than the vertical one. These correlations together with joint probability density distributions seem to indicate the following mechanism of the surface renewal; the large turbulence eddy wells up toward the free surface spreads horizontally and renews the free surface. Then it exchanges heat and mass across the free surface and subsequently plunges back into the bulk flow with the streamwise velocity larger than its mean value $\bar{U}$.

In order to estimate the contribution of the surface renewal eddies to the vertical heat transfer, the heat flux by the downward motion with the negative θ-spikes less than the threshold level was calculated. This was divided by the total heat flux at $y/\delta = 0.90$ and is plotted in Fig. 10. The time fraction of the appearance of the surface renewal eddy was also shown in the same diagram. Despite the small time fraction less than 0.1, the contribution of the surface renewal eddy to the heat transfer attains more than 60%. Therefore it may be concluded that the large surface renewal eddy controls the heat and mass transfer across the free surface.

A simple model for mass transfer

The predictions of the turbulent mass and heat transfer across an air–liquid interface are important for the wide range of engineering and geophysical applications. Therefore many models have been presented to estimate the coefficients of mass and heat transfer. These models contain empirical parameters which have been determined from gas absorption measurements but not from turbulence measurements.

Introducing the results of the turbulence measurements, we here present a simple surface renewal model which was originally proposed by Dankwerts [13]. In this model, the following assumptions are used:

(i) The large energy-containing eddy renews the free surface and controls mass transfer at the free surface.

(ii) The rate of the surface renewal is approximately equal to the frequency corresponding to $k = 56$.

For the surface renewal eddy in a stirred vessel with 295 mm i.d. and a single, flat bladed stirrer of length 80 mm, the wavenumber of $k = 52$ was obtained by applying the method used in the previous section. The stirrer speed was 104 r.p.m. and the Reynolds number based on the stirrer speed was 21,600. The value of $k = 52$ is very close to $k = 56$ obtained in the open channel flow. For the high Reynolds number flow ($Re = 34{,}000$) in a large open channel 1.2 m wide, 0.1 m deep and 8.0 m long, the surface renewal rate corresponding to $k = 60$ was also obtained. These results may support the validity of the assumptions mentioned above.

Following the surface renewal model of [13], the liquid-side mass transfer coefficient k_L is given by

$$k_L = \sqrt{(D_L s)}. \tag{4}$$

From the definition of the wavenumber, the frequency of surface renewal can be written as

$$f = k\bar{U}_{suf}/2\pi. \tag{5}$$

Putting $s = f$, we obtain

$$k_L/\sqrt{(D_L \bar{U}_{suf})} = \sqrt{(k/2\pi)} \tag{6}$$

When $k = 56$ was used, a value of about 3.0 was finally obtained.

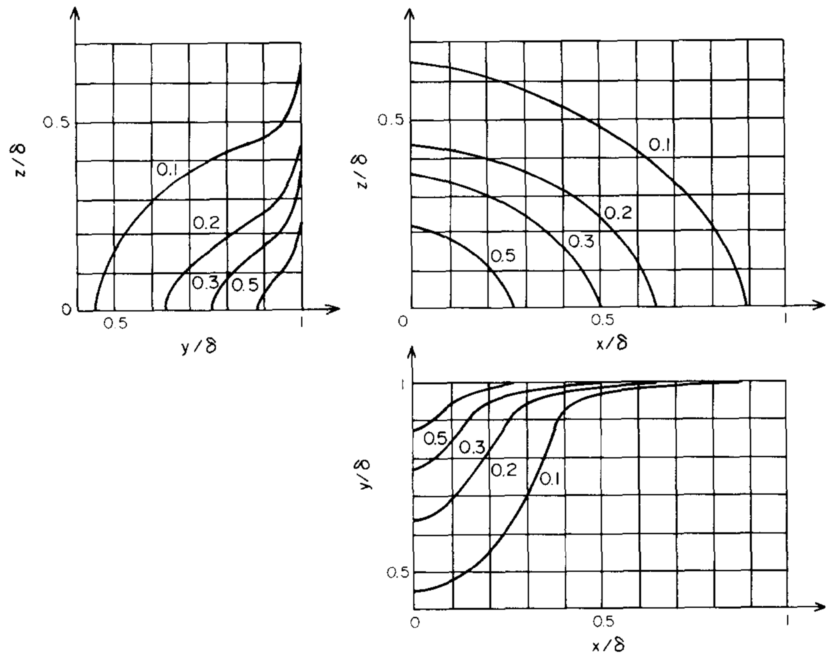

FIG. 9. Iso-correlation contours of the temperature fluctuations between the fixed point on the free surface and an arbitrary point located inside the flow and/or on the free surface.

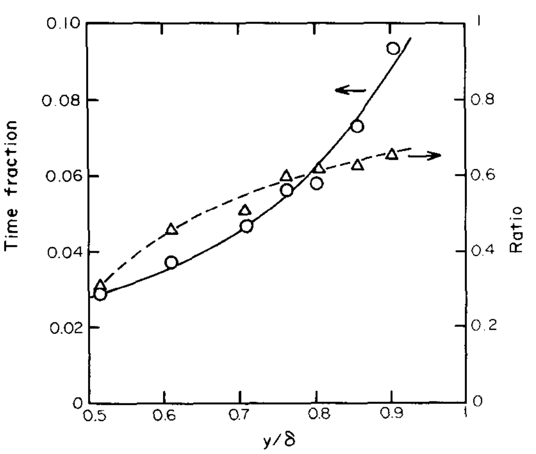

FIG. 10. Ratio of the vertical heat flux by the surface renewal eddies to the total heat flux at $y/\delta = 0.90$, and the time fraction of the appearance of the surface renewal eddy.

Following the form on the left-hand side of equation (6), mass transfer coefficients obtained by the previous investigators were rearranged and plotted against *Re* in Fig. 11. Here, the mean surface velocity $\bar{U}_{suf}$ was estimated by using the logarithmic law for water tunnel flows and natural stream. In the case of stirred vessel, it is difficult to estimate the surface velocity and so only the data of [5] were used because of the high Reynolds number turbulent flow with the surface velocity close to the stirrer speed. From the figure, it can be seen that the measured values of $k_L/\sqrt{(D_L \bar{U}_{suf})}$ are close to 3.0 and independent of the Reynolds number, through the data were scattered.

CONCLUSION

Turbulence structure at the free surface in open channel flow has been investigated experimentally and

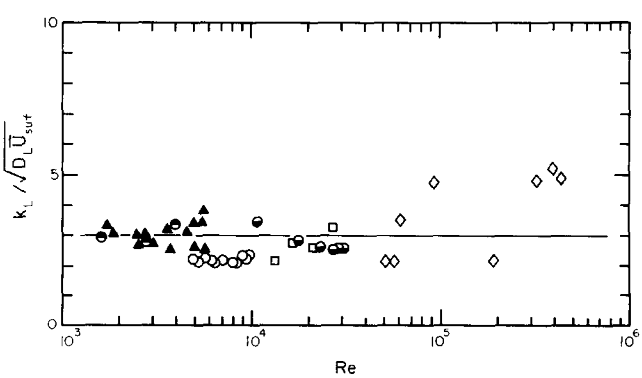

FIG. 11. Comparison of the values of k_L from equation (6) with those of previous experiments. —— from equation (6). ○, CO_2–water water tunnel [1]; ◒, CO_2–water water tunnel [2]; ▲, CO_2–water water tunnel [3]; ◇, O_2–water natural stream [4]; □, O_2–water stirred vessel [5]; ◓, CO_2–water inclined plate [7].

a simple theoretical model has been presented. The main results can be summarized as follows:

(1) At and near the free surface vertical velocity fluctuations are damped and so the redistribution of the energy of the vertical motion promotes the lateral and streamwise motions.

(2) Large, energy-containing eddies with a size close to the integral scale of turbulence replace the free surface and control the heat and mass transfer across it.

(3) A simple surface renewal model was presented, its assumptions confirmed by the turbulence measurements; this model predicted the observed results of the liquid-side mass transfer coefficients k_L with satisfactory accuracy.

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STRUCTURE DE TURBULENCE ET MECANISME DE TRANSPORT A LA SURFACE LIBRE DANS UN ECOULEMENT EN CANAL OUVERT

Résumé—On étudie les champs de vitesse et de température très près de la surface libre dans un écoulement en canal ouvert. Des températures instantanées à la surface libre et près d'elle sont mesurées par un thermomètre avec un scanner à infrarouge et par une résistance thermométrique. Les fluctuations de vitesse sont mesurées simultanément par vélocimétrie laser Doppler. Les résultats montrent que près de la surface libre, les mouvements verticaux sont amortis tandis que les mouvements longitudinaux et transversaux sont amples. La surface est renouvelée par des tourbillons turbulents de taille proche de l'échelle de longueur intégrale et qui sont responsables du transfert de chaleur et de masse à travers la surface libre. On présente un modèle simple de renouvellement de la surface basé sur ces mesures et la prédiction du coefficient de transfert massique montre un accord satisfaisant avec des données connues de l'absorption de gaz dans un canal à eau, dans un mélangeur et dans des écoulements sur plaque inclinée.

TURBULENZSTRUKTUR UND TRANSPORTMECHANISMUS AN DER FREIEN OBERFLÄCHE EINER OFFENEN KANALSTRÖMUNG

Zusammenfassung—Die Temperatur- und Geschwindigkeitsfelder in unmittelbarer Nähe der freien Oberfläche einer offenen Kanalströmung wurden untersucht. Die momentanen Temperaturen an und nahe der Oberfläche wurden mit einem Infrarot- bzw. einem Widerstandsthermometer gemessen. Die Geschwindigkeitsfluktuation wurde gleichzeitig mit dem Laser-Doppler-Verfahren gemessen. Die Ergebnisse zeigen, daß nahe der freien Oberfläche die Vertikalbewegungen gedämpft werden, während sich die Längs- und Querbewegungen verstärken. Die Oberfläche wird durch turbulente Wirbel von der ungefähren Größe des integralen Längenmaßstabs erneuert, die für den Wärme- und Stofftransport durch die Oberfläche verantwortlich sind. Ein einfaches Oberflächenerneuerungsmodell, das sich auf diese Turbulenzmessungen stützt, wurde vorgestellt. Die hiermit berechneten Stoffübergangskoeffizienten auf der Flüssigkeitsseite zeigten gute Übereinstimmung mit früheren Absorptionsmeßwerten von Gasen bei Strömungen in Wasserkanälen, Rührkesseln und an schrägen Platten.

СТРУКТУРА ТУРБУЛЕНТНОСТИ И МЕХАНИЗМ ПЕРЕНОСА НА СВОБОДНОЙ ПОВЕРХНОСТИ ПРИ ТЕЧЕНИИ В ОТКРЫТОМ КАНАЛЕ

Аннотация — Исследуется распределение температуры и скорости вблизи свободной поверхности при течении в открытом канале. Мгновенные значения температуры на свободной поверхности и вблизи нее измерялись соответственно термоанемометром с инфракрасным развертывающим устройством и термометром сопротивления. Пульсации скорости одновременно измерялись лазерным допплеровским анемометром. Результаты показывают, что у свободной поверхности вертикальные движения затухают, а аксиальные и радиальные усиливаются. Подпитка энергией свободной поверхности осуществляется за счет переноса к ней турбулентных вихрей, размер которых примерно равен интегральному масштабу длины и которые обусловливают тепло- и массоперенос через свободную поверхность. Представлена простая модель «обновления поверхности», основанная на результатах измерения турбулентности. Расчеты коэффициента массопереноса со стороны жидкости хорошо согласуются с ранее полученными данными по абсорбции газов в трубе с движущейся жидкостью, в сосудах с мешалками и при течении на наклонной поверхности.