

Turbulent characteristics in a baffled contact tank

Caractéristiques turbulentes d'un réservoir mélangeur à déflecteurs

K. SHIONO, *Department of Civil and Building Engineering, Loughborough University, UK.*

E. C. TEIXEIRA, *Department of Hydraulics and Sanitary Engineering, Technological Centre, Universidade Federal do Espírito Santo, Brazil*

ABSTRACT

Turbulence measurements were undertaken using a two-component laser Doppler anemometer (LDA) in a serpentine contact tank (CT) commonly used for water chlorination. A detailed examination of turbulent parameters was carried out and showed the significant effects of the baffle lee and the inlet and outlet of the tank on the CT's hydraulic efficiency. Turbulence levels were quantified along the tank and were found to be considerably high in the tank inlet, first and second compartments and to be decaying rapidly in the latter compartments. The decay rate of turbulence along the tank is similar to that of the grid generated turbulence. The turbulence generation mechanisms in the first compartment were identified using comparative studies of the turbulence characteristics in the backward-facing step flow obtained by Eaton and Johnston (1981) and in the plane wall jet obtained by Rajaratnam (1976). The main contribution of the high turbulence level in the compartment was found to be due to shear generated turbulence in the upper layer. Tracer measurements were also carried out and an optimum dispersion coefficient at the outlet of the tank was found to be $16.2 \text{ cm}^2/\text{s}$. From the Marske and Boyle's equation (1973) in this tank, for $b = 37$, the dispersion coefficient is $2.9 \text{ cm}^2/\text{s}$, which is one order smaller than that obtained from this study.

RÉSUMÉ

Des mesures de turbulence par anémomètre laser Doppler à deux composantes ont été effectuées dans un réservoir mélangeur à labyrinthe communément utilisé pour la chloration de l'eau. Un examen détaillé des paramètres de turbulence a été entrepris et a montré l'influence significative de l'effet d'obstruction des déflecteurs et de l'entrée et de la sortie du réservoir sur le rendement hydraulique. Les niveaux de turbulence ont été quantifiés et se sont révélés importants à l'entrée du réservoir et dans les premier et deuxième compartiments pour diminuer rapidement dans les derniers compartiments. Le taux de décroissance de la turbulence le long du réservoir est similaire à celui de la turbulence générée par un grillage. La génération de turbulence dans le premier compartiment a été caractérisée à l'aide d'études comparatives sur les caractéristiques de la turbulence pour un écoulement face à une marche par Eaton et Johnston (1981) et pour un jet contre une paroi par Rajaratnam (1976). La contribution principale au niveau élevé de turbulence semble dû à la turbulence engendrée par le frottement dans la couche supérieure de l'écoulement. Des mesures à l'aide de traceurs ont également été menées et ont indiqué que le coefficient optimal de dispersion à la sortie du réservoir était de $16.2 \text{ cm}^2/\text{s}$. D'après l'équation de Marske et Boyle (1973), dans ce réservoir, pour $b = 37$, le coefficient de dispersion est de $2.9 \text{ cm}^2/\text{s}$, ce qui est inférieur d'un ordre de grandeur à la valeur obtenue dans la présente étude.

Introduction

There is increasing concern about the inefficient use of chlorine for drinking water and wastewater disinfection due to the formation of potentially carcinogenic compounds, which originate from the residual chlorine in a CT. The design and operational deficiencies of tanks are attributed to the residual chlorine as shown by Hart & Gupta (1978), Marske & Boyle (1973), Sepp (1981) and Trussell & Chao (1977). Chlorine contact tanks are usually treated as "black boxes" without considering the flow behaviour within the tanks. The most common method for evaluating hydraulic efficiency is the interpretation of flow through tracer curves obtained at the tank outlet. In the few cases where details of the flow field have been attempted, quantification of the flow in the tanks' inlet and outlet regions were either omitted (Louie & Fohrman, 1968), or inaccurate (Falconer & Tebbutt, 1986), due mainly to the lack of an adequate device for measuring velocity in three-dimensional flow fields. However, the configuration of the tank's inlet and outlet and the existence and arrangements of baffles in the tank can attributed more complex structure to the flow meaning that the mixing and transport processes of chlorine are also greatly influenced by turbulent levels, flow circulation and dead zones along the tank.

A number of turbulence measurements in open channel flows has been undertaken (e.g. Nezu and Rodi, 1986, for a simple rectangular channel study, Shiono and Knight, 1991, for compound channel studies, and Shiono and Muto, 1993, for a meandering channel study). Also turbulence measurements for settling tanks have been carried out by Lyn & Rodi (1990) and McCorquodale, Mousi & El-Sebakhy (1988) in order to acquire an understanding of the hydrodynamics. These measurements showed considerable interest in the inlet region of the tank because the flow at the tank inlet is highly turbulent. However reports in the literature on measurements of turbulence in a chlorine contact tank seems to be non-existent.

The characterisation of the turbulent field of a water body is a very helpful tool for the understanding of mixing processes taking place in contact tanks [Jobson and Sayre, 1970; Lyn and Rodi, 1990]. As a turbulence-free flow is among the characteristics of the ideal flow regime in contact tanks, the characterisation of the turbulent field can be of great help for the contact tank design. In this paper, various flow regions possessing significant levels of turbulence in the model contact tank used in this study are first identified, and then the causes for the significant levels of turbulence analysed.

Revision received March, 1999. Open for discussion till February 28, 2001.

Experimentation tank and velocity data acquisition

The experiments were undertaken in two cross-baffled model contact tanks, which have the same configuration as that for the Emsbay Water Treatment Plant, designed and operated by Yorkshire Water, Western Division, England, UK. The linear scale ratios between the Emsbay tank and two model tanks are 8:1 and 4:1 (see Plate 1 for 4:1) and configuration and dimensions of the model tank in Figs.1. The flow structures between the two scale models were very similar (see Teixeira, 1993), hence the result of the 8:1 tank is only presented here.

The flow rate of the model tank was 1.17 l/s. This flow rate corresponds to the maximum established flow rate in the prototype tank, and was determinant by the use of the Froude similarity law. However Froude scaling may be not valid for the first few compartments since jet flow is dominated. This flow rate yielded a tank mean water depth of 536 mm, and an approximate cross-sectional mean velocity, U_o , equal to 10.0 mm/s. An illustration of some of the terms used throughout this and further sections referring to the tank geometry is given in Fig.1.

A two-component laser Doppler anemometer (LDA) was used for measuring instantaneous velocities at a point. The LDA was based on a 300 mW argon ion laser power source, operated in a back scatter mode and accounted for reversing flows. Because the velocity in most regions of the experimentation tank was very low, and the laser power output on the probe head was not high enough to yield a good return signal, a suspension of silver coloured powder ($d_{50} = 20 \mu\text{m}$) in water was used as a seeding agent continuously injected into the tank.

An investigation was carried out in order to define the record lengths, T , of the instantaneous velocity time series to be used for the determination of mean velocity, turbulent intensity and Reynolds shear stress at a point. For this, four velocity time series of 15 min each were obtained, one for a point within a relatively fast flow region and the other within a slow flow region. Characteristics of these four time series are given in Fig.2. From each of these time series fourteen sub-time series of record length 1 min, 2 min,, and 14 min were generated. An analysis of the errors, Es , of determination of the mean velocity and turbulent intensity relative to the mean velocity and turbulent intensity corresponding to $T = 15$ min was carried out for all these record lengths.

At P1 in the shear region, for $U = 15.7\text{cm/s}$ and $u' = 2.8\text{cm/s}$, the errors for the 2min record length were 0.3% and 0.7% respectively. According to the analysis of a burst period of turbulence in open channel flow given by Nezu and Nakgawa (1993), the expression for the burst period, Tb , is $Tb = 1.5-3 d/U_{max}$, with a maximum velocity, U_{max} , and a thickness of the boundary layer, d . In this region the burst period becomes about 2-4 sec. For the 2 min record length, there are 30-60 burst events. The error for 30-60 burst events is very small in this case (less than 1% error) although Nezu and Nakagawa recommended 100 burst events. These errors suggest that the 2 min record length of the record is long enough. Furthermore the errors in the mean velocities and turbulent intensities were smaller than 5% for T for 2 min, where the local mean velocity

is much greater than the cross-sectional mean velocity U_o (= 10.0 mm/s).

At P2 in the slow flow region, for $U = 0.4\text{cm/s}$ and $u' = 1.1\text{cm/s}$, the errors for the 2 min record length were 16% and 40% respectively. According the analysis for slower flow regions, the limits for the errors are equal to 10% and 5% when the corresponding values of T are greater than, or equal to, 6 min and 10 min, respectively. There seem to be large errors in slower flow regions for the 2 min record length, but the trend of the flow structure was not significantly different from that for the longer record lengths. We decided to use a 2 min record length for showing flow structures.

Data analysis

Turbulence characteristics

The analysis presented in this section is based on the normalised turbulent intensities u'/U_o , v'/U_o and w'/U_o of the longitudinal, transverse and vertical velocity components, respectively, and the normalised Reynolds stress components $-\overline{uv}/U_o^2$ and $-\overline{uw}/U_o^2$. The record length of the velocity time series used to obtain these turbulent parameters was equal to 2 min. It should be remembered that the 2 minute length may give a large error of turbulence parameters in slower flow regions, but the pattern of the parameters should not change greatly since the magnitudes are very small. Fig. 3 shows the mean flow, turbulent intensities and Reynolds stress of the vertical plane on the centre line of compartment 1. The mean flow field expressed by velocity vectors is shown in Fig 3a. The figure shows the existence of two recirculation flow regions, the first one is located just downstream of the inlet weir and the second occupies the whole compartment 1. Detailed information of the mean flow pattern in the model tank can be found in Teixeira (1993).

The highest levels of turbulence were found in the region between the inlet weir and the tank inlet section (Fig.3 b), where the reasons for this are mainly attributed to the impact of the flow past the weir onto the bottom of the approach channel, and the re-circulating flow in this region, as can be seen in Fig.3a. The values of u'/U_o and w'/U_o found in this region range approximately between 2.0 and 9.0, and 2.5 and 7.0, respectively.

Compartment 1

The levels of turbulence in the top flow region of compartment 1 are still quite significant in comparison to those in the region between the inlet weir and the tank inlet section, in which the values of u'/U_o and w'/U_o range approximately between 1.5 and 3.5, and 1.5 and 2.5, respectively; see Figs.3 (b and c). The magnitude and distribution of the normalised Reynolds stress $-\overline{uw}/U_o^2$ given in Fig.3d indicate that shear is an important characteristic of the flow in this region. Thus, the turbulence in this flow layer seems to be due to both shear generated turbulence locally, and transport of turbulence from the region between the inlet weir and the tank inlet section. The turbulence in compartment 1 is also appreciable

in the layer adjacent to wall *TW-3*, which appears to be due to wall-generated turbulence.

A schematic representation of both the two-dimensional rearward-facing step flow studied by Etheridge and Kemp (1978) and the flow on the vertical plane of compartment 1 are given in Figs.4 (a and b). The main differences in geometry and flow condition between the two flows are briefly described below (the following notations are used: TS = this study, and EKS = Etheridge and Kemp's study):

1. Velocity profiles on the upstream side of the step-section, i.e., at $x/Hs = 0$ (Hs is the step height)
EKS: the flow is a well developed boundary layer and the thickness of the boundary layer (d) is approximately equal to Hs .
TS: the flow at the inlet is complex due to the weir effect as seen in Fig. 3a.
2. Heights of the step relative to the value of the water depth are $Hs = 6.7\%$ of Ht and $Hs = 84\%$ of Ht for the EKS and TS cases respectively.
3. For the *EKS* case, the length of the channel downstream of the step-section of the step-section is greater than the value of the reattachment length (Xr); Xr ($= 5$ times Hs) is the value of x which defines the end of the re-circulating flow region. For the TS case, the length of the channel from the step-section to wall *TW-3* is only 2.1 times Hs .

Since Ht/Hs in this study is about 1.19, and smaller than the value corresponding to Etheridge and Kemp's study, the comparison between the two flows was carried out for values of z/Hs smaller than 1.19. The parameters used in the analysis are the normalised mean velocity U/Um , and the normalised Reynolds stress $-\overline{uw}/Um^2$, where Um is the maximum value of U for each velocity profile within the range $0 < z/Hs < 1.19$. The record length for the time series used in the computation of U and $-\overline{uw}$ was 15 min since slower flow regions were included in the region of interest. The measurements of the time series were undertaken at $x/Hs = 1.0$, and the results of U/Um and $-\overline{uw}/Um^2$ for the two flows are given in Figs.4 (c and d), respectively.

A comparison of the mean velocity profiles at $x/Hs = 1.0$, given in Fig.4 c, indicates that there is a quite good similarity between the two mean flows within $z/Hs > 0.45$. Below this value of z/Hs , however, the two velocity profiles differ completely in shape, indicating very distinctly different behaviour of the two flows. It can be noticed that while in Etheridge and Kemp's study the absolute value of U decreases continually to zero from $z/Hs = 0.45$ towards the bottom of the channel, it increases continually to a value around $Um/2$ in this study. This indicates that the high reversing flow rate in the bottom layer of compartment 1 is entirely a consequence of the deflection of the flow in the top layer towards the bottom of the tank by wall *TW-3* (see Fig. 3), rather than partially due to a contribution from the re-circulating flow found in rearward-facing step flows, which originated as a result of the flow separation from the bottom of the channel at the step-section, i.e. at $x/Hs=0$.

With respect to the turbulent field, although Fig.4d shows that there exists a similar overall behaviour between the two ($-\overline{uw}/Um^2$) – profiles, two distinct aspects of them can be noticed; they are:

1. The values of z/Hs corresponding to the maximum value of ($-\overline{uw}/Um^2$) are 1.00 and 1.08 for the EKS and TS cases respectively.
The reason for the aforementioned value of z/Hs being greater in this study is an aspect of the flow condition at $x/Hs = 0$, i.e., the flow direction towards the water surface.
2. The maximum values of $-\overline{uw}/Um^2$ are 0.0111 and 0.0145 for the EKS and TS cases respectively.

The reasons for the maximum value of $-\overline{uw}/Um^2$ in this study being about 30% bigger than the corresponding value in Etheridge and Kemp's study may be related to the fact that: (1) while in this study the thickness of the shear layer above the step is about $0.19Hs$ at $x/Hs = 1.0$, it is about Hs in Etheridge and Kemp's study, meaning that the shear layer above the step in this study is relatively thinner than in theirs; and (2) while the velocity gradient (dU/dz) over the top shear layer in this study is constant and slightly greater than in Etheridge and Kemp's study, it decreases gradually until $z/Hs = 2.0$ in theirs, indicating that our maximum velocity Um may not correspond to theirs or the flow above the step level in this study is slightly more sheared than in theirs. Despite this, the velocity and shear stress profiles are in good agreement. The analysis therefore shows that, in the top layer, the turbulence is mainly generated by the shear.

A Comparison Between the Flow in the Layer Adjacent to Wall TW-3 and the Plane Wall Jet

Significant turbulence levels near wall *TW-3* were noticed in Fig. 3(c-d). In order to examine the turbulence generation in this region a comparative analysis of the flow with a plane turbulent wall jet flow was also carried out. The mean velocities, intensities, and Reynolds stress used in this analysis were also determined from 15 minute velocity time series, and correspond to values of z/Ht and y/Lt equal to 0.5 and 0.05, respectively, and various values of $DfTW3/Wt < 0.2$; $DfTW3$ is the distance of a velocity sampling point from wall *TW-3*. The values of U/Uo , W/Uo , u'/Uo , w'/Uo , and $-\overline{uw}/Uo^2$ are plotted in Figs.5 (a and b). In order to compare the mean flow in the layer adjacent to wall *TW-3* and the mean flow of the plane wall jet, calculated downward velocity values of W/Wm are shown in Fig.5c with the velocity distribution of the entire wall jet given by Verhoff [in Rajaratnam, 1976], that is,

$$\frac{W}{Wm} = 1.48\eta^{1/7}[1 - erf(0.68\eta)] \quad (1)$$

in which η is equal to $DfTW3/b$; b is the value of $DfTW3$ corresponding to W equal to $Wm/2$ in the jet's free-mixing region; Wm is the maximum value of W ; $erf(x)$ is the error function of x . As can be noticed in Fig.5a, all the measurements were undertaken in the free-mixing region. This was due to the dimension

of the laser submerged probe. Thus, to obtain W_m the following procedure was adopted: (1) linear extrapolation of the measured W -velocity profile until wall $TW-3$; and (2) determination of W_m as being the mean between the maximum W measured value and the value of W at wall $TW-3$, as a result of the extrapolation procedure. The values of W_m/U_0 and b/Wt were, then, equal to 11.25 and 0.072, respectively.

Fig.5c shows that there is a quite good similarity between the shape of the measured and Verhoff's profiles. The ratio between the measured and Verhoff's mean velocities ranges from 0.93 to 0.96 within $0.2 < h < 0.5$, and from 0.96 to 1.0 within $0.6 < h < 1.1$. This indicates that there is a better degree of agreement between the two profiles within the latter h -range. A comparison between the turbulent characteristics of the two flows is given in Fig. 5d, based on the values of $-\overline{uw}/Um^2$, both measured and given by Rajaratnam (1976). A very good similarity between the turbulent characteristics of the two flows is observed within $0.2 < h < 0.8$. On the other hand, an increasing deviation between the two Reynolds stress profiles for $h > 0.8$ can be noticed. This indicates a loss of similarity between the turbulent characteristics of the two flows for values of h greater than 0.8.

The comparative analyses undertaken above show that the flow in the layer adjacent to wall $TW-3$ presents a good similarity to the plane turbulent wall jet, for values of h smaller than 0.8, or in terms of Wt , for $DfTW3/Wt < 0.06$. It can be noted in Fig.5b that: (1) the highest values of u/U_0 and w/U_0 in this flow region are found within the area bounded by $DfTW3/Wt < 0.06$; (2) this limiting value of $DfTW3/Wt$ approximately corresponds to the maximum shear stress $-\overline{uw}/Um^2$. These final remarks are good indicators that the significant levels of turbulence in this flow layer are mainly due to wall-generated turbulence.

Turbulent kinetic energy budget

It has been mentioned in the previous section that the reasons for the relatively high levels of turbulence in the top flow layer of compartment 1 might be the locally shear generated turbulence, and the transport of turbulence from the region between the inlet weir and the tank inlet section by the mean current. Thus, in order to examine this and gain an understanding of the mechanisms of transport, generation and dissipation of turbulence in this flow layer, an analysis of the conservation equation for the turbulent kinetic energy was carried out. This analysis was also applied to the bottom flow layer.

The locations considered here have more or less a unidirectional flow in the x direction and have relatively small lateral velocity, $V \sim 0$. The conservation equation of turbulent kinetic energy for steady flow can be reduced to the form, for the $X-Z$ plane:

$$U \frac{\partial q^2}{\partial x} + W \frac{\partial q^2}{\partial z} + \overline{uw} \frac{\partial U}{\partial z} + \varepsilon + \frac{\partial}{\partial z} (\overline{q^2 w} + \overline{pw}) = 0 \quad (2)$$

[1] [2] [3] [4]

in which q^2 is the turbulent kinetic energy; p is the pressure fluctuations; \overline{uw} is the velocity fluctuations product; u and w are

the velocity fluctuations in the longitudinal and vertical directions, respectively; ε is the turbulent energy dissipation rate; x and z are the Cartesian co-ordinates in the longitudinal and vertical directions, respectively; [1] the total advection of kinetic energy (ADVEC); [2] generation (GENER); [3] viscous dissipation (DISSI); [4] diffusion (DIFFU); and the over-bar represents time average.

The record length for the measurements of the velocity time series used to obtain the parameters U , W , q^2 , u , w and ε was 15min. The turbulent energy q^2 was taken as the mean value of the two following approaches: $q^2 = 0.5 (u^2 + 2.w^2)$, Van Atta and Chen (1968), and $q^2 = 0.75 (u^2 + w^2)$, Lyn and Rodi (1990). In open channel flow, turbulent intensities are normally $u' > w' > v'$. Nezu and Nakagawa (1993) used the Kolmogorov spectrum law to evaluate the dissipation rate of turbulent kinetic energy. They maintained that this method gave a more accurate dissipation rate than other methods. It should be noted that the equation is applicable only to 2-D flow. In this flow condition from the turbulence characteristic analysis, 2-D flow can be assumed at the top and bottom layers of the mid section in the first compartment. The dissipation rate ε was therefore obtained by averaging a number of ε values in the inertial subrange of the 1-D spectrum $E(k_1)$, which obeyed Kolmogorov's energy spectrum law [Nezu and Nakagawa (1993)]:

$$E(k_1) = \alpha \varepsilon^{2/3} k_1^{-5/3} \quad (3)$$

in which $k_1 = 2\pi f/U$ is the wave number in the x -direction where $\alpha = \text{constant}$. $f = \text{frequency}$ and $U = \text{local velocity}$. The α value equal to 0.5 is usually referred to in the literature and was adopted in this study.

The advection, generation and dissipation terms in Eq.1 were determined for various z positions over the top and bottom flow layers, at the half of the first compartment, $x/Wt = 0.5$. The diffusion term was then calculated by difference. The results of the calculations are shown in Figs. 6 (a and b). The overall balances of turbulent kinetic energy for both top and bottom layers were determined by integrating each term in Eq.1 over the thickness of each flow layer, and the results are presented in Table 1. Generation and dissipation are the most significant terms in the overall energy balance; see Fig. 6 (a and b). They account for 100% and 81% of the total gain and loss, respectively, of the turbulent kinetic energy in the top flow layer, and 77% and 68%, respectively, in the bottom layer; see values in Table 1.

The absolute value of the total gain or loss of kinetic energy (AVTGL) in the bottom region, shown in Table 1, is about 10.5% of AVTGL in the top flow region. This and Fig. 3d indicate that the shear-generated turbulence in the top region is much greater than the bed-generated turbulence. The overall advection of turbulent energy is small in the top flow layer (= 2.5% of AVTGL), but it is about 25% of AVTGL within the upper 1/3 part of the this flow layer, i.e., within $z/Ht > 0.94$; see values in Table. 2. Therefore the advection of turbulence from the weir effect at the inlet could be significant near the water surface.

Fig. 6b shows that when approaching the bottom of the tank, the loss of turbulent energy due to diffusion becomes more significant than the loss due to viscous dissipation. In the case of the top flow region, the viscous dissipation is, for all the points over the vertical, greater than any other corresponding loss of kinetic energy.

Compartments 2–8

Figs. 7 and 8 show the mean flow, turbulent intensities and Reynolds stress of the horizontal planes at the top, mid-depth and bottom layers of compartment 2. As can be seen from Fig. 7(a-c), the mean flow patterns on the horizontal planes are totally different. This is mainly due to the deflection of the Compartment 1 upper layer flow at the wall *TW-3*. It can be seen from Figs. 7 (d-f) that the regions of most significant levels of turbulence in compartment 2 are located in the first half of the compartment length; i.e., within $x/Wt > 0.5$. They correspond to the horizontal re-circulating flow regions in the top and mid-depth layers, (see Figs. 7.a and 7b) and the bottom region immediately downstream from the lee of baffle.1 (see Fig. 7c). The values of u'/U_0 in these regions range approximately from 1.0 to 2.5, which are slightly smaller than those in the high shear region of compartment 1. A reason for the significant levels of turbulence in the bottom region seems to be the turbulence generated as a result of the flow deflection from the lee of baffle 1. Isovels of the normalised Reynolds stress component, $-\overline{uv}/U_0^2$, for the re-circulating flow regions in the top and mid-depth layers are given in Figs. 8a and b. They show that the values of $-\overline{uv}/U_0^2$ in these regions are still appreciable in comparison to those of $-\overline{uw}/U_0^2$ found in the top flow layer in compartment 1. This indicates that the turbulence in these re-circulating flow regions is partially due to shear. The interaction between the reversing and stream-wise flows in this layer is another source of turbulence generation. This suggests that plug flow cannot be expected in this compartment because intensive mixing occurs locally.

The mean flow field and isovels of u'/U_0 in the vertical planes at the centre line of compartments 3 and 4 are given in Figs. 9. Large mean flow in the upper and bottom layers in compartments 3 and 4 respectively can be observed from Fig. 9 (a and b). This is mainly caused by the flow deflection at the walls; however this trend disappears along the tank and the flow of the vertical plane at the centre line of the compartments becomes more or less uniform after compartment 4. Fig. 9 (c and d) shows that the values of u'/U_0 in compartment 3 are smaller than 1.5, and smaller than 0.75 in compartment 4. This indicates the occurrence of an overall decaying of the levels of turbulence in the longitudinal direction. The turbulent intensity in compartment 4 became fairly uniformly distributed over the vertical plane. It was also noticed that the mean longitudinal velocities were uniformly distributed. The turbulence tends to be maintained by two other sources of turbulence generation from compartment 5 onwards. They are the flow acceleration-deceleration in the vicinity of the transition sections between compartments, and the re-circulating flows behind the baffles in

compartments (5-8) shown in Fig. 10 a. The values of u'/U_0 in each of the compartments (5-7) range from 0.4 to 0.6 as shown Fig.10 b.

Turbulence decay along tank

An analysis of the overall turbulence decay at the centre line along the tank was carried out, based on the analysis of both the measured and exponential best-fitted profiles of the depth averaged intensity u'/U_0 , given in Fig. 11. The velocity time series used for calculating the depth averaged values of u'/U_0 were selected from those on the vertical plane in Fig.3. The verticals considered, 90 in total, were those on the central line of the serpentine channel formed by the tank's compartments and the transition sections between compartments.

The turbulence tends to be conservative in compartment 1. This kind of behaviour has also been observed along the re-circulating flow regions of rearward-facing step flows [Eaton and Johnston, 1981; Ruderich and Fernholz, 1986]. A very accentuated exponential decay from the beginning until the mid-length of compartments 2, and moderate decay from the latter location to the beginning of compartment 4 are observed. The corresponding decay exponents (n) (see the equation in Fig. 11) are equal to 4.5 and 1.68, respectively, which are both greater than the maximum value of n (~1.43) found in grid-generated turbulence studies [Mohamed and LaRue, 1990]. This may be owing to the significant production of turbulence in the compartment 2 as observed in Fig. 7. There is an overall very gradual decay along compartments (4-7), with decay exponent (n) equal to 0.27. However, an increase in the level of turbulence in each of these compartments can be observed around the transition sections between compartments, due to both the flow acceleration/deceleration, and the re-circulation regions behind the baffles. These generation sources serve to maintain the turbulence levels in each compartment whereas the grid-generated turbulence has no turbulence generation source along the channel.

Length without wall jet and free shear effect

It was shown in the previous sections that there exist wall- and free shear- jet flows in compartment 1, identified by comparative analyses of the flow with a rearward-facing step flow and a plane wall jet flow. These jet flows were generated by the initial flow condition at the inlet of the tank. The flow will never be plug flow needed for the design of an ideal contact tank, as long as jet flow exists along compartments. Therefore plug flow in this tank cannot be achieved in the first few compartments; however there is no influence of the jet flow in some compartments. In order to investigate a length over which the wall- and free shear- jet flows are no longer dominant, the compartments were divided into three layers such as a top, mid and bottom layers mainly associated with the free shear turbulence, slower flow and wall generated turbulence respectively. The averaged velocity of each layer in the compartments was plotted in Fig. 12. The figure clearly shows a decay of the velocity along the compartments approaching the section mean velocity U_0 . A number of studies on plane

wall jets (i.e. Pakke, 1957 and Swamy and Bandyopadhyay, 1975) suggests that the velocity, U , in the flow direction, x , is expressed by a power law, i.e. $U \propto x^{-\alpha}$. As can be seen from Fig. 3a), Fig. 7 c) and Fig. 9 a) & b), the effect of the free shear- and wall- generated turbulence mainly occurs at the top and bottom layers in alternate compartments. For the top layer in odd compartments it is the free shear generated turbulence and for the bottom layer in even compartments it is the wall- generated turbulence. The layer velocities, U_a , of the those top and bottom layers at the mid alternate compartments were plotted in a log-log form up to compartment 6, since the top and bottom layer values are almost the same after compartment 6, and are shown in Fig. 13. The graph shows an exponential decay of the velocity with the distance, x . The linear best fitted line was found to be given by: $\log(U_a.U_o) = -0.800 \cdot \log(X_{sc}/L_{sc}) - 0.148$ as shown in Fig. 13. From the fitted equation, a length without effect of the jet flow in the flow field, i.e. $U_a/U_o = 1.0$, is $X_{sc}/L_{sc} = 0.653$, which corresponds to compartment 6. This location is at the transition of the flow from the jet to the open channel flow and may be a minimum length requirement for hydraulic efficiency in this tank.

Dispersion coefficient

The two major variables that govern the effectiveness of chlorine disinfection of micro-organisms are the contact time and the chlorine dosage rate to the kinetics of micro-organism deactivation. Wehmer & Wilhelm (1956) derived a formula, which can be used for designing real flow chemical reactors in a more rational way, i.e. by using relationships between the residence time distribution (RTD) of the reactors and the kinetics of the disinfection. Trussell & Chao (1977) give a more elaborate design formula for the estimation of disinfection efficiency. The use of either of the formulae for designing CT to satisfy a desired degree of disinfection requires a knowledge of the value of the dispersion coefficient. For example, the dispersion coefficient is commonly used to predict a flow through curve at the outlet of a tank. From the flow through curve analysis, Marske and Boyle (1973) suggested that the design of tank $b = L/B$ is determined by $d = 0.14/b$ where $d =$ dispersion index $= Dl/(U_oL)$, $Dl =$ dispersion coefficient, $U_o =$ mean velocity, $L =$ tank length and $B =$ width. They found $b = 40$ to be best for the design of a tank in terms of hydraulic efficiency. This value was considered to be independent of the configuration of the tank.

In order to find the variation of the dispersion coefficient along the compartments, a tracer dye was instantaneously injected in the approach channel. Concentration distributions at compartments 5,6,7 and 8 were measured with time. A number of the experiments were repeated to obtain concentration distributions at 15 locations in each cross section of a compartment. Concentration distributions for 9 locations in compartment 5 are shown in Fig. 14. The 9 locations were one at the centre and two near the side walls at each of the top, middle and bottom layers. The results show that the dye is fairly well mixed at the cross section. The 15 concentrations at each cross section were averaged. The averaged concentration distributions are shown in Fig. 15

together with the curves predicted by using Fischer's equation (1968). The equation is:

$$C(x_2, t) = \int_0^{\infty} U_o C(x_1, \tau) \frac{\exp(-t_v)}{[4\pi Dl(t_{g2} - t_{g1})]^{0.5}} d\tau \quad (4)$$

where

$$t_v = [U_o(t_{g2} - t_{g1} - t + \tau)][4Dl(t_{g2} - t_{g1})]^{-1.0}$$

$C(x_1, \tau) =$ observed concentration distribution at x_1 , at time τ from the moment of tracer injection.

$C(x_2, t) =$ observed concentration distribution at x_2 , at time t from the moment of tracer injection.

$\tau =$ time variable of integration.

$t_{g1}, t_{g2} =$ mean times of passage of the tracer cloud, past the upstream (x_1) and downstream (x_2) sections respectively.

The dispersion coefficients of compartments 6, 7 and 8 were estimated using the distribution of the cross sectional averaged concentration at compartment 5 with its optimisation. It should be noted that the use of Fischer's equation requires flow conditions of constant flow across a section and a constant dispersion coefficient. From the above flow analyses, at least the vertical distributions of the mean velocity are more or less uniform, and the decay rates of the mean layer velocity and the mean turbulent intensity after compartment 4 are very slow. Because there exist noticeable transverse variations of velocity, the flow conditions may therefore not exactly satisfy the use of Fischer's equation. The predicted results show good agreement between the measured and predicted concentrations. The optimum dispersion coefficients at compartments 6,7 and 8 were found to be 22 cm²/s, 18.5 cm²/s and 16.2 cm²/s respectively. It is of interest that the result at the outlet of the tank is close to the Elder's value of 15 cm²/s. This dispersion coefficient was estimated from Elder's equation based on 2-D flow:

$$D = 5.93u^*Ht$$

where $u^* =$ friction velocity.

The friction velocity u^* was obtained from the Manning equation with a Manning coefficient of 0.01 for the treated wood of the tank and was 4.69×10^{-2} cm/s. Although the flow in compartment 8 is three-dimensional because of the effects of baffles, narrow channel and tank outlet, the dispersion coefficient estimated from Elder's equation is close to its measured value. This indicates that the flow non-uniformity in compartment 8 does not affect strongly the dispersion process. From the Marske and Boyle's equation in this tank, for $b = 37$, the dispersion coefficient is 2.9 cm²/s, which is one order smaller than that obtained from this study. However Trussell and Chao (1977) modified the Marske and Boyle's equation to $d = 0.14 kn/b$, where $kn =$ non-uniformity coefficient, using prototype data. With the dispersion coefficient, $Dl = 16.2$ cm²/s, $U_o = 0.01$ m/s and $L/B=37$, then the non-uniformity coefficient, kn , becomes 5.6. The decay of the jet flow mainly caused by the wall and

bed friction suggests that the equation may need the introduction of more hydraulically related parameters, such as hydraulic radius. At this stage there are not enough data to draw any conclusions since only one tank configuration was studied here.

Comments on numerical models

In recent years, the use of numerical models for predicting flows, and transport and dispersion of disinfectants in contact tanks has received some attention. Falconer and Lui, 1987 and 1988 developed two-dimensional depth averaged models to predict flow patterns throughout the tanks and found significant disparities between measured and predicted values at the tanks' inlet and outlet regions because the flows in those regions are highly three dimensional. Wang (1995) used a two-dimensional depth averaged $k-\epsilon$ numerical model to predict the flow in this tank and found also significant disparities between the measured and predicted values in the compartments 1 to 3. However the predicted flow patterns and the measured data in the latter compartments are in good agreement. This is understandable from our turbulent flow results that the flows are highly three dimensional in the inlet, compartments 1 and 2, and outlet regions, and are not highly three-dimensional in the latter compartments. This suggests that it is necessary to develop a 3-D numerical model with turbulent closure models for improving a predictive capability of flow in a complex contact tank. Although the tank configuration in this study is very specific, this experimental result presented here may also help those who are considering developing such turbulent models. Particularly when coupling the momentum and solute transport equations, the ratio of turbulent eddy diffusivity to eddy viscosity, the so called "Turbulent Schmidt number", is required. The ratio is different for shear flow and wall turbulence flow as reported by Rodi, 1980 and Shiono et. al. 1998. As different turbulence characteristics in compartment 1 has been found, particular attention needs to be paid to the ratio in numerical models.

Conclusions

Turbulence measurements were carried out along a serpentine contact tank. Its configuration was based on a site-specific contact tank of the Embsay Water Treatment Plant, England, UK. The following conclusions were obtained :

- i Significant levels of turbulence were found in several flow regions along the tank. Various sources of turbulence generation were identified and are shear, bed, and wall generated turbulence, the deflection of the flow from a baffle lee, the acceleration/ deceleration of the flow when crossing a transition section between compartments, and the re-circulating flows behind the baffles in compartments. (5–8).
- ii The comparative analysis between the mean flow on the vertical plane of compartment 1 with the mean flow of a rearward-facing step flow showed that the two flows were very similar within $z/Hs > 0.45$. For values $z/Hs < 0.45$ their behaviours were different. This disparity between

the two flows indicated that the high reversing flow rate in the bottom layer of compartment 1 was entirely a consequence of the deflection of the flow in the top layer towards the bottom of the tank by wall TW-3, rather than partially due to a contribution from the re-circulating flow found in rearward-facing step flows.

- iii A comparison between the flow in the layer adjacent to wall TW-3, compartment 1, with the plane turbulent wall jet showed that the two flows were very similar within $DfTW3/Wt < 0.06$. This comparative analysis also showed that the significant levels of turbulence in this flow region were mainly due to wall-generated turbulence.
- iv The balance of the turbulent kinetic energy equation in the region of highest levels of turbulence in the tank, the top layer of compartment 1, revealed that shear-generated turbulence locally accounted for 100% of the overall gain of turbulent kinetic energy. Viscous dissipation, diffusion, and advection were responsible for 81%, 16.5%, and 2.5%, respectively, of the overall loss of kinetic energy in this flow layer.
- v The analysis of the variation of the depth averaged values of dimensionless turbulent intensity u'/Uo along the tank showed that the overall turbulence tended to be conservative in the first compartment, and decayed very rapidly in compartment 2. From compartment 2 to compartment 4 it decayed moderately similar to that of the grid generated turbulence, and very gradually from compartment 4 onwards.
- vi The layer velocity along the flow direction, x , was found to be expressed by a power law. The equation is $\log(Ua/Uo) = -0.800 * \log(Xsc/Lsc) - 0.148$. From the equation, a location without effect from the jet flow in the flow field was found to occur after compartment 6.
- vii The optimum dispersion coefficients at compartments 6,7 and 8 were found to be 22 cm²/s, 18.5 cm²/s and 16.2 cm²/s respectively. From the Marske and Boyle's equation in this tank, for $b = 37$, the dispersion coefficient is 2.9 cm²/s, which is one order smaller than that obtained from this study. The equation needs the introduction of more hydraulically related parameters.

Acknowledgements

The authors are grateful to Prof. R.A. Falconer and Mr. A.F.J. Daron from the Department of Civil Engineering – University of Bradford-UK, where the research was conducted. Grateful acknowledgements are also to CAPES of the Brazilian Ministry of Education, SERC-UK and Yorkshire Water for their financial support, and to BIRAL-UK for both financial and technical support.

References

- BAKKE, P., (1957), "An experimental investigation of a wall jet", *Journal of Fluid Mechanics*, Vol. 2, pp. 467–472.
- EATON, J.K., and JOHNSTON, J.P., (1981), "A review of research on subsonic turbulent flow reattachment", *AIAA Journal*, Vol. 19, No. 9, pp. 1093-1100.

- ETHERIDGE, D.W. and KEMP, P.H., (1978), "Measurements of turbulent flow downstream of a rearward-facing step", *Journal of Fluid Mechanics*, Vol. 86, Part 3, pp. 545–566.
- FALCONER, R.A., and LIU, S.Q., (1987), "Mathematical model study of plug flow in a chlorine contact tank", *Journal of the Institution of Water and Environmental Management*, Vol. 1, No. 3, pp.279–290.
- FALCONER, R.A., and LIU, S.Q., (1988), "Modelling solute transport using the QUICK scheme", *Journal of Environmental Engineering*, ASCE, 114, (1), pp.3–20.
- FALCONER, R.A., and TEBBUTT, T.H.Y., (1986) "A theoretical and hydraulic model study of a chlorine contact tank", *Proceedings of the Institution of Civil Engineers (UK)*, Vol. 81, Part 2, pp. 255–276.
- JOBSON, H.E., and SAYRE, W.W., (1970), "Vertical transfer in open channel flow", *Journal of the Hydraulics Division*, ASCE, Vol. 96, No. HY3, pp. 703–724.
- HART, F.L., and GUPTA, S.K., (1978), "Hydraulic analysis of model treatment units", *Journal of the Environmental Engineering Division*, ASCE, 104, (EE4), 785–798.
- LOUIE, D.S., and FOHRMAN, M.S., (1968), "Hydraulic model studies of chlorine mixing and contact chambers", *Journal of the Water Pollution Control Federation*, 40, (n.2/part 1), 174–184.
- LYN, D.A., and RODI, W., (1990), "Turbulence measurements in model settling tank", *Journal of Hydraulic Engineering*, ASCE, 116, (1), 3–21.
- MARSKE, D.M., and BOYLE, J.D., (1973), "Chlorine contact tank design - a field evaluation", *Water & Sewage*, January, pp. 71–77.
- MCCORQUODALE, J.A., MOURS, A.M., and EL-SEBAKHY, I.S., (1988), "Experimental study of flow in settling tanks", *Journal of Environmental Engineering*, ASCE, 114, (5), 1160–1174.
- MOHAMED, M.S., and LARUE, J., (1990), "The decay power law in grid-generated turbulence", *Journal of Fluid Mechanics*, Vol. 219, pp. 195–214.
- NEZU, I. and NAKGAWA, H. (1993), "Turbulence in Open Channel Flows", *IAHR Monograph*.
- NEZU, I. and RODI, W., (1986), "Open channel flow measurements with a laser Doppler anemometer", *Journal of Hydraulic Engineering*, ASCE, Vol. 112, No. 5, pp. 335–355.
- RAJARATNAM, N., (1976), *Turbulent Jets*, Development in Water Science, 5, Elsevier Scientific Publishing Company.
- REYNOLDS, A.J., (1976), *Turbulent Flows in Engineering*, John Wiley & Sons Ltd..
- RODI, W., 1980, *Turbulence models and their application in hydraulics – a state of the art review*, The IAHR- section on Fundamentals of Division II: Experimental and Mathematical Fluid Dynamics.
- RUDERICH, R., and FERNHOLZ, H.H., (1986), "An experimental investigation of a turbulent shear flow with separation, reverse flow and reattachment", *Journal of Fluid Mechanics*, Vol. 163, pp. 283–322.
- SEPP, E., (1981), "Optimisation of chlorine disinfection efficiency", *Journal of the Environmental Engineering Division*, ASCE, 107, (EE1), 139-153.
- SHIONO, K. and KNIGHT, D. W., (1991), "Turbulent open channel flows with variable depth across the channel", *Journal of Fluid Mechanics*, 222, pp. 617–646.
- SHIONO, K. and MUTO, Y., (1993), "Secondary flow structure for in-bank and over-bank flows in trapezoidal meandering compound channel", *Proceedings of the 5th International Symposium on Refined Flow Modelling and Turbulence Measurements*, Paris, France, 7-10 September, pp. 645–652.
- SHIONO, K., FENG, T. and MUTO, Y., (1998), "Reynolds stress and flux measurements in open channel flow using a laser induced fluorescence technique", *Proceedings of 7th International Symposium on flow modelling and turbulence measurements*, Tainan, Taiwan, October, pp.117-124.
- SWAMY, N.V.C. and BANDYOPADHYAY, P. (1975), "Mean and turbulence characteristics of three dimensional wall jets", *Journal of Fluid Mechanics*, Vol. 71, pp. 451–562.
- TEIXEIRA, E.C., (1993), "Hydrodynamic Processes and Hydraulic Efficiency of Chlorine Contact Units", Ph.D. Thesis, Department of Civil Engineering, University of Bradford, U.K..
- TOWNSEND, A.A., (1976), *The Structure of Turbulent Shear Flow*, 2nd Edition, Cambridge University Press.
- TRUSSELL, R.R., and CHAO, J-L., (1977), "Rational design of chlorine contact facilities", *Journal of the Water Pollution Control Federation*, April, pp. 659–667.
- VAN ATTA, C.W., and CHEN, W.Y., (1968), "Correlation measurements in grid turbulence using digital harmonic analysis", *Journal of Fluid Mechanics*, Vol. 34, Part 3, pp. 497–515.
- WANG, H., (1995), "Numerical modelling of flow and disinfection processes in Chlorine Contact Tanks", Ph.D. thesis, Department of Civil Engineering, Bradford University.
- WEHMER, J.F. and WILHELM, R.H. (1956), "Boundary condition of flow reactor", *Chemical Engineering Science*, Vol. 6 pp. 89–93.

Notations

<i>AVTGL</i>	Absolute value of total gain or loss of kinetic energy
<i>D</i>	Dispersion Coefficient
<i>E</i>	Energy spectrum
<i>EKS</i>	Etheridge and Kem's study
<i>Es</i>	Error
<i>H_s</i>	Step height at the inlet
<i>H_t</i>	Water depth
<i>K</i>	one dimensional wave number
<i>L_t</i>	Tank length
<i>n</i>	Decay exponent
<i>p</i>	pressure fluctuation
<i>q</i>	Turbulent kinetic energy
<i>T</i>	Length of time record
<i>TS</i>	This study
<i>U</i>	Time averaged longitudinal velocity
<i>U_o</i>	Sectional mean velocity
<i>U_m</i>	Maximum velocity
<i>V</i>	Time averaged lateral velocity
<i>W</i>	Time averaged vertical velocity
<i>W_m</i>	Maximum velocity
<i>W_t</i>	Compartment length
	Reynolds stress
<i>u', v', w'</i>	Turbulent intensities
<i>u*</i>	Friction velocity
<i>x</i>	Longitudinal distance
<i>y</i>	Lateral distance
<i>z</i>	Vertical distance
<i>Greek</i>	
α	constant (= 0.5)
ε	Turbulent energy dissipation rate