# Evaluating the effect of inlet arrangement in settling tanks using the hydraulic efficiency diagram

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## Abstract

Flow-through curves (FTC) were obtained experimentally in 2 rectangular settling tank models consisting of an inlet slot and an outlet weir. The most important of the FTC characteristics were calculated and plotted on a diagram, which is called the hydraulic efficiency diagram (HED). Using the HED it was shown that the hydraulic efficiency of the tank improves by placing the inlet slot away from the mid-depth, either close to the surface or preferably close to the bottom. Hydraulic efficiency improves further by the use of inlet deflectors, whose position (distance and submersion) is not very critical provided that the deflectors are effective and divert the incoming jet towards the bottom. Some flow characteristics (length of recirculation areas) were measured and correlated to FTC characteristics.

## Nomenclature

| | | |
|---|---|---|
| a | = | constant defined in Eq. (8) |
| b | = | constant defined in Eq. (8) |
| C | = | concentration of tracer[$M/l^3$] |
| $C_o$ | = | M/V average tank concentration[$M/l^3$] |
| CM | = | Completely mixed |
| c | = | $C/C_o$ normalised concentration of tracer[-] |
| $c_{max}$ | = | maximum value of E(t) [-] |
| d | = | fraction of the stagnant region defined in Eq. (8)[-] |
| $Dt_a$ | = | width of the FTC at E(t)=a[-] |
| E(t) | = | coordinate of the FTC defined by Eq. (3)[-] |
| F(t) | = | coordinate of the cumulative FTC defined by Eq.(4)[-] |
| FTC | = | flow-through curve |
| H | = | depth of the tank[l] |
| HBP | = | hold back parameter |
| L | = | length of the tank[l] |
| M | = | injected mass of tracer[M] |
| Mo | = | $t_{90}/t_{10}$ Morril index[-] |
| HED | = | hydraulic efficiency diagram |
| p | = | fraction of plug flow defined in Eq. (8)[-] |
| PF | = | plug flow |
| PFP | = | plug flow parameter defined by Eq. (7)[-] |
| q | = | Q/(WL) overflow rate[$l/T$] |
| Q | = | inlet flow rate[$l^3/T$] |
| R | = | UH/v Reynolds number[-] |
| $R_{ec}$ | = | recovery ratio defined by Eq. (2)[-] |
| s | = | height of the inlet slot[l] |
| SEG | = | segregation parameter[-] |
| T | = | time[T] |
| $T_{exp}$ | = | duration of the experiment[T] |
| $T_{TH}$ | = | V/Q theoretical detention time[T] |
| t | = | $T/T_{TH}$ normalised time defined by Eq. (3)[-] |
| $t_a$ | = | time at which a% of the tracer has passed[-] |
| $t_{exp}$ | = | $T_{exp}/T_{TH}$[-] |
| $t_g$ | = | average time[-] |
| $t_{max}$ | = | time for $c_{max}$[-] |
| U | = | Q/(WH) mean flow velocity in the tank[$l/T$] |
| v | = | kinematic viscosity[$l/T^2$] |
| V | = | WHL = volume of the tank[$l^3$] |
| $V_{ar}$ | = | variance of the E(t) [-] |
| W | = | width of the tank [l] |

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## Introduction

The removal efficiency of settling tanks is largely a function of the hydraulic characteristics of the tank. The term " hydraulic characteristics" refers to the kinematics of flow through the tank and thus to the velocity field. The calculation of local velocities is difficult, expensive and time- consuming to perform (Adams and Stamou,1988), so that the analytical development of a realistic flow field for a settling tank is not a simple operation. It is possible, however, to employ a simple tracer technique, which yields kinematic results that are functions of the general flow field involved. The tracer technique permits the development of the FTC, whose characteristics provide important information on the hydraulic behaviour of the tank under examination.

For the derivation of the FTC a known mass (M) of tracer is injected instantaneously at the inlet of the tank. The resulting plot of the tracer concentration (C) vs. time (T) at the outlet of the tank is the FTC. The FTC is essentially the probability density function (pdf) of the detention times of the liquid (and solid) particles within the settling tank. The FTC is usually expressed in non-dimensional and normalised form by dividing concentrations by the average concentration of tracer in the tank ($C_o$) and times by the theoretical detention time ($T_{TH}$), while the area under the FTC is set equal to unity.

FTCs can be used for various purposes. From an FTC the actual (most probable) detention time and other characteristic parameters, such as the dispersion coefficient can be determined. These parameters can be used as inputs to solids removal efficiency models ranging from simple empirical equations (CIRIA,1973) to advanced mathematical models for solids transport (Stamou et al.,1989) to determine the removal efficiency of the tank. FTCs can also be superimposed with quiescent column settling curves to determine the removal efficiency (Villemonte et al.,1966) or used for the verification of mathematical models describing the tracer transport and mixing (Stamou,1991). By comparing the shapes and characteristics of FTCs, the effect of a parameter of a settling tank such as tank dimensions, inlet and outlet configurations, flow characteristics (e.g.overflow rate) on its hydraulic efficiency can

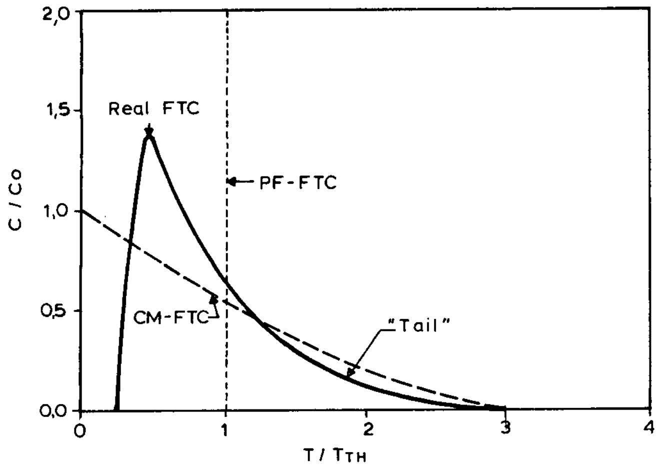


***Figure 1***
*Ideal and real FTCs*

be examined (McCorquodale,1980).

In the present work FTCs were obtained experimentally in 2 rectangular settling tank models, consisting of a slot inlet and an outlet weir. The parameters examined were the position of the inlet slot and the use and position of inlet deflectors. Some flow characteristics (length of recirculation areas) were also measured and correlated to FTC characteristics. No settling measurements were performed in this study to be compared with FTC characteristics.

## Theoretical consideration

### Ideal and real FTCs

The statistical description of a real FTC is always related to 2 ideal cases, for which the settling behaviour is known. These cases are the PF FTC and the CM FTC. In the PF situation the tracer mass moves through the tank with a constant U without mixing and reaches the outlet in the theoretical detention time. The concentration of the outlet stream is infinite at $T=T_{TH}$, because the injection time is assumed infinitesimal and zero for all other times (Fig.1). For the CM situation the injected mass of tracer is assumed to mix instantaneously and completely at T=0 with the entire volume content of the tank to form a tracer concentration equal to $C_o$. As time elapses the outlet concentration decays exponentially (Fig.1).

In a real settling tank with a slot inlet (with or without deflector) and an outlet weir (see the streamline patterns of Fig.2) the FTC produced at the outlet has the typical shape of Fig.1 being affected by short-circuiting and mixing in the tank. Short-circuiting is defined in analogy with electrical networks as the very early (compared to $T_{TH}$) appearance of the tracer at the outlet of the tank. Mixing in the tank is created by the large-scale turbulence produced in the large recirculation areas and the small scale moving eddy turbulence occurring in the largest portion of the tank, where the flow is fully turbulent. Therefore, the level of mixing in a tank with large recirculation areas and high Reynolds number will be more intense than in a tank with small recirculation areas and low Reynolds number. Generally, short-circuiting controls the initial arrival time and mixing controls the spreading of the FTC. As shown in Fig.1 a typical FTC appears as a rather strongly skewed function of T with a "tail" in the large values of T. This tail, which is due to the delayed appearance of the ever-dwindling amount of

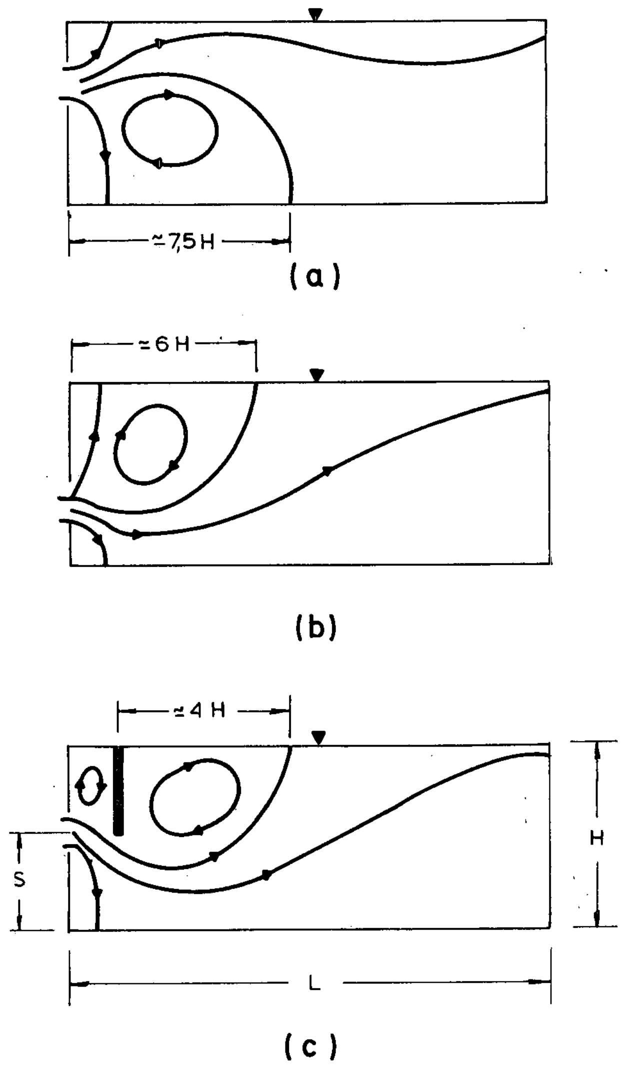


***Figure 2***
*Typical streamline patterns*
*(a) s-pattern, (b) l-pattern and (c) d-pattern*

tracer in the large recirculation areas resembles the CM FTC.

The mass conservation constraint for a real FTC implies that the mass of tracer entering the tank equals the mass of tracer leaving the tank, i.e.:

$$M = \int_{T=0}^{T=\infty} Q(T)\ C(T)\ dT \tag{1}$$

Because a single FTC experiment lasts a finite time ($T_{exp}$); measurement and calibration errors occur; and the sampled stream at the outlet may not be representative due to tank three-dimensionality, the amount of tracer recovered at the outlet is usually not that which was injected. For this reason a recovery ratio is defined as:

$$R_{ec} = (1/M) \int_{T=0}^{T=Texp} Q(T)\ C(T)\ dT \tag{2}$$

To obtain a non-dimensional FTC, E(t), independent of measurement errors, concentrations C(T) are normalised by the average tank concentration $C_o$, time t by the theoretical detention time $T_{TH}$

and the area under the FTC by $R_{ec}$, i.e.:

$$E(t)=C(T)/(R_{ec}C_o) \text{ and } t=T/T_{TH} \qquad (3)$$

A cumulative FTC, F(t), may be defined similarly to the familiar distribution function of statistics

$$F(t)=\int_0^t E(t)dt \qquad (4)$$

F(t) tends to behave better experimentally than E(t), because of its integral nature. F(t) values represent the probability that a part of the liquid in the tank has a detention time less or equal than t. Conservation of mass requires F(t )=1,0 and thus for a normalised FTC $F(t_{exp})=1,0$.

### FTC characteristics

In this section a critical presentation of the most important FTC characteristics, which are encountered in the literature is made. These characteristics have been grouped into 4 broad categories of indicators:

- short-circuiting;
- mixing-dispersion;
- degree of PF; and
- efficiency times ( shown in Fig.3).

Generally, the usefulness of these indicators is an attempt to quantify the degree to which a particular FTC approaches PF or CM behaviour. The general belief that the closer the FTC approaches PF, the better the removal efficiency, is adopted in this paper. This is, however, not always true since an FTC does not contain any information on scour or particle-particle interaction, such as coagulation. Therefore, 2 settling tanks with identical FTCs will have the same removal efficiency, only if they have identical particle characteristics.

#### *Short-circuiting indicators*

These are the initial arrival time ($t_0$),the time at which 10% of tracer has passed the outlet ($t_{10}$) and the HBP. $t_{10}$ is more often used because it is more easily determined experimentally than $t_0$. Generally, the larger the values of $t_0$ and $t_{10}$, the less short- circuiting and the closer the flow approximates the desired PF situation. For example, the FTC for the CM case has $t_0$=0 and thus very large short-circuiting and the FTC for the PF case has $t_0$=1 and thus zero short-circuiting. This example shows clearly that short-circuiting is always associated with mixing. HBP is defined as the area under the F(t) curve from t=0 to t=1

$$HBP=\int_0^1 F(t)\, dt \qquad (5)$$

High HBP values indicate that much of the tracer mass passes rapidly through the tank by a short-circuit route.

#### *Mixing indicators*

Time-differences ($t_{75}$-$t_{25}$ and $t_{90}$-$t_{10}$ or $Dt_{0.1}$ and $Dt_{0.5}$) or time-ratios (such as the Morril Index,Mo=$t_{90}/t_{10}$) and the variance of E(t), $V_{ar}$,

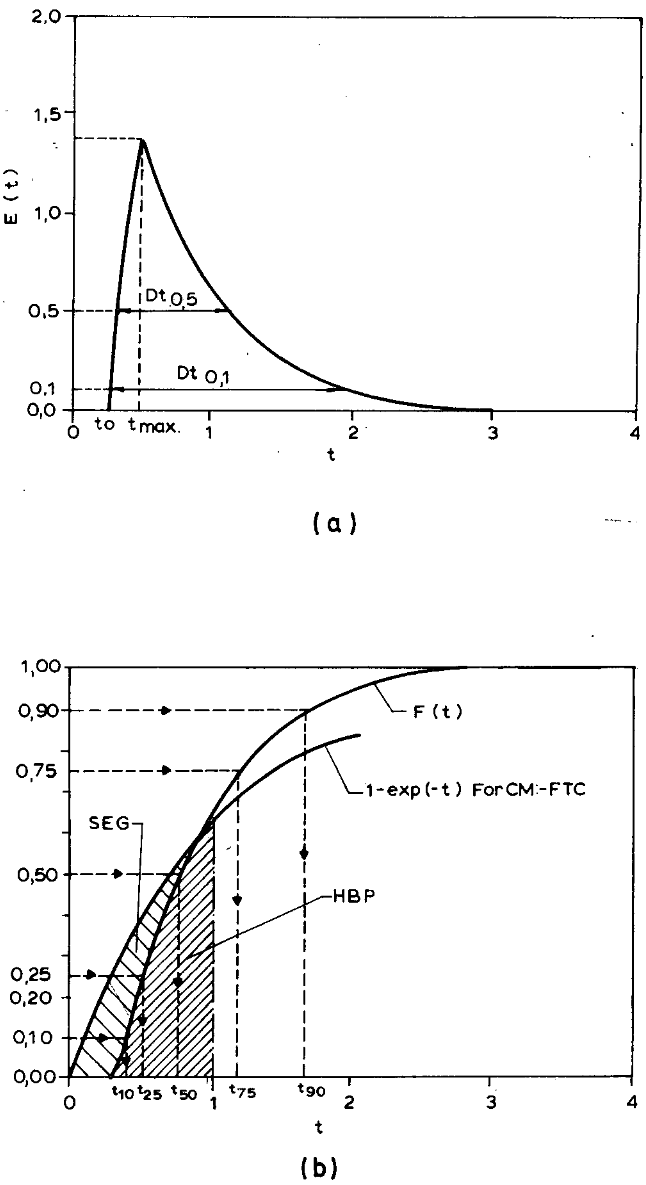


*Figure 3*
*FTC characteristics*
*(a) E(t) characteristics, (b) F(t) characteristics*

are measures of the width of the FTC and are therefore considered as estimators of the mixing in the tank. $V_{ar}$ is defined as:

$$V_{ar}=\int_0^1 (t-1)^2\, E(t)\, dt \qquad (6)$$

Mo is extremely sensitive to short-circuiting, because of the presence of $t_{10}$ in the denominator. $V_{ar}$'s calculation is very sensitive and dependent on the long tail of the FTC. The variance is a somewhat more mathematically rigorous parameter than the previous measures of the width of E(t), but probably has not been used more for reasons of experimental uncertainty. For example, instead of $(t-1)^2$, it may be better to use $(t-t_g)^2$, since $t_g$ rarely obtains its theoretical value (unity).

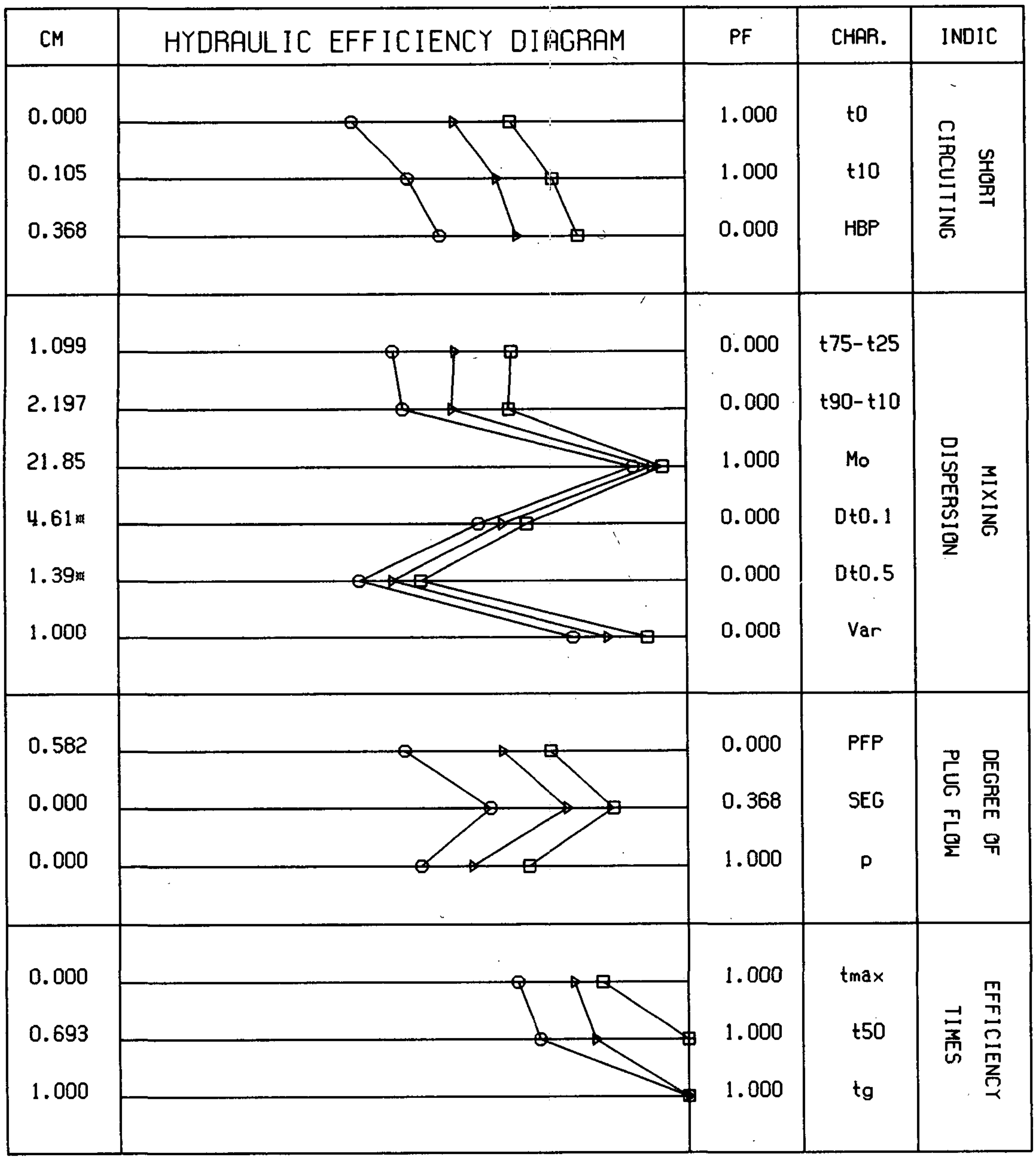


***Figure 4***
*HED for H/s=1,1( □ ); 1,3( Δ ) and 1,7( O )*

***PF indicators***

The following indicators attempt, through integral means, to establish effective "fractions" of the PF and CM conditions: the PFP, the SEG and the p. PFP is defined as follows:

$$PFP=1-\int_0^1 F(t)\, t\, dt \Big/ \int_0^1 F(t)\, dt = HBP/F(1) \qquad (7)$$

SEG is defined as the area between the F(t) and the F(t) for CM from t=0 to the t value, where the 2 curves cross. Low PFP and high SEG values indicate that the flow approaches PF conditions. Unfortunately both strong short-circuiting and PF lead to high values of SEG.

According to Rebhun and Argaman (1965) the tank volume can be divided into zones with the hydraulic characteristics of PF, CM and stagnant regions. Stagnant regions are considered those where there is no fluid motion. Such zones do not exist, but are a concept designed to aid comparison of various flow patterns. An F(t) can be approximated by the following expression:

$$F(t)=1-\exp[-a(t-b)] \qquad (8)$$

where:

$$a=1/[(1-p)(1-d)] \quad \text{and} \quad b=p(1-d)$$

p is the fraction of PF, 1-p is the fraction of CM and d is the fraction of stagnant regions. The coefficients a and b are found from a curve fit to E(t) plotted in semi-log coordinates.

*Efficiency times*

In almost all removal efficiency theories and empirical models the theoretical detention time is used as one of the parameters to determine the removal efficiency. However, the theoretical detention time is not the most representative value of detention time and other times such as the $t_g$, the time at which half of the tracer mass has passed ($t_{50}$) and the most probable time ($t_{max}$) can be used as more representative. $t_{max}$ is the easiest parameter to determine experimentally, but due to measurement uncertainty displays much more scatter than $t_{50}$. Furthermore, $t_g$ is practically never equal to unity and is strongly a function of the duration of the FTC experiment ($t_{exp}$).

*Hydraulic efficiency diagram*

The indicators described above attempt to give a quantitative description of the degree to which either the PF or CM model describes a settling tank, in which the only information available is the FTC. While each indicator is sensitive to slightly different anomalies of the FTC, there does not seem to be a consensus on which indicators are to be preferred. For this reason the authors have collected these indicators into a diagram called the HED, shown later in an application (Fig.4). The HED is therefore a graphical representation of flow conditions in a settling tank and can be formulated on information obtained solely from tracer studies. The limits on the HED are normally the values for the CM and PF reactors, except the indicators $Dt_{0.1}$ and $Dt_{0.5}$ for which the limits are selected so that the values for the real FTC lie in the HED.

HED's application is not restricted to settling tanks, but to all reactors, whose hydraulic efficiency is to be determined.

## Experimental procedure and analysis of data

FTC experiments were performed in 2 model settling tanks: Model A, located in the Laboratory of Applied Hydraulics of the National Technical University of Athens, Greece and Model B, in the Institute of Hydromechanics of the University of Karlsruhe, Germany. Both experimental models had the geometry of a typical and simple rectangular sedimentation tank with a slot inlet and an outlet weir.

### Experimental procedure

The measurement technique applied involved the use of coloured fluorescent tracers. Rhodamine WT was used as a tracer selected on the basis of a literature survey (Stamou and Adams,1988) and arbitrary tests. A known amount of tracer was injected at the inlet of the model tanks over a relatively short time approaching a pulse input, through a series of small diameter pipes. A very well distributed line source was produced ensuring a good spanwise distribution of tracer, which was required for the outlet stream to be considered as two-dimensional and the results at a single sampling point could be used. The effluent at the outlet of the tank was sampled continuously at a single point using a Model III Turner fluorometer. The continuous sample was fed to the fluorometer by gravity. To check the uniform distribution of tracer at the outlet a series of FTCs was obtained at various transverse locations. The comparison of these FTCs showed no noticeable differences. Therefore, the tranverse distribution of tracer was satisfactory and basin two-dimensionality was ensured.

The fluorometer was connected to a digital voltmeter and thus the output of the fluorometer system was a voltage proportional to the concentration. The proportionality curve was found by calibration. The data were recorded on a plotter (for Model A) or transferred to a PC-HP-310 computer via an IEEE 488 bus (for Model B). The transfer of data to the PC-IBM-AT for model A was not possible directly, but only after digitalisation of the recorded FTC graph via a CALCCOMP. The data were stored in the computer memory for post-processing.

### Analysis of data

For each case examined 8 to 10 FTC runs were performed. An average FTC was built as follows:

- normalisation of each E(t) using Eq.(3);
- construction of F(t) from each E(t) using Eq.(4);
- averaging of all F(t)s to produce an average F(t); and
- differentiating the average F(t) to produce the final average E(t).

Then the characteristic indicators were calculated and the HED was subsequently constructed with the help of a program written in FORTRAN language. It was noted during the pre-experiment phase that some indicators ($t_g$ and $V_{ar}$) were highly sensitive to the duration of the experiment as evidenced by the existence of the FTC tail. For this reason it was decided to adopt a consistent duration of $t_{exp}$=2.5 for all FTC experiments, so that the results were comparable. It is very important to note that results from different experimental studies are comparable only if they are normalised in the same way and have the same experimental duration. Furthermore, FTC data with recoveries significantly different from 1,0 must be regarded with scepticism. In this study only data with $R_{ec}$=0,90-1,10 were used.

### Measurement errors and uncertainty

A theoretical method is described in Adams and Stamou (1988), according to which the statistical uncertainty for all indicators was calculated to be less than 5%, except the indicators near the peak, where the error was approximately 10%. In addition to this analysis, a statistical survey was performed on a series of 12 FTCs obtained at the same sampling point under exactly the same conditions. For the characteristic times and time differences the deviation was found to be equal to 0,02 to 0,04 (3 to 6%), except for $t_{max}$, whose deviation was 0,03 to 0,06 (5 to 10%). McCorquodale (1980) has found similar uncertainties (0,03 and 0,10 respectively). For other indicators like HBP, PFP and SEG the uncertainty was 0,01 to 0,02 (8 to 11%) and for the peak value of E(t) it was 0,17 (10%).

## Results and discussion

### Flow patterns

The flow pattern in the tanks was always asymmetric and independent of the degree of geometrical symmetry, being characterised by a short and a large separation region (Fig.2). For inlet slots placed close to the surface (high H/s values) the large separation region is formed near the bottom (s-pattern, Fig.2a), while for inlet slots placed close to the bottom (low H/s values) it is formed near the surface (l-pattern, Fig.2b). For inlet slots placed close to the mid-depth both flow patterns can be observed (see Adams and

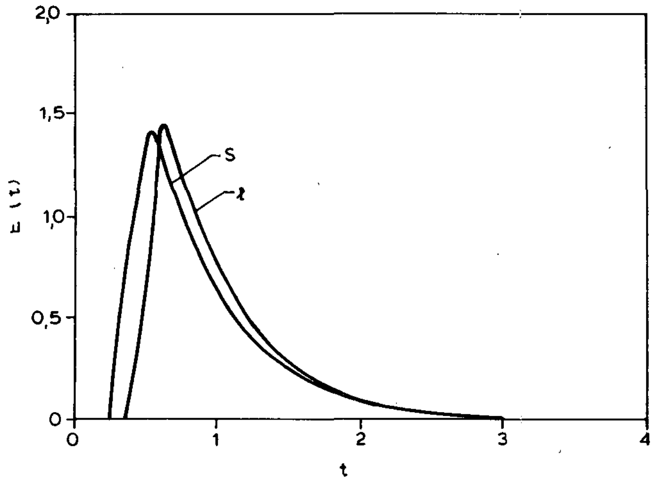


*Figure 5*
*FTCs for H/s=2,0 - Effect of flow pattern*

Stamou, 1989 for more details). Experiments performed in both models have shown that the long separation length is approximately equal to 7,5 depths for the s-pattern and 6 depths for the l-pattern. The short reattachment length is significantly smaller (1 depth) and is relatively unaffected by the type of flow pattern. The use of inlet deflectors shortens the reattachment length behind the deflector (d-pattern,Fig.2c) to 4 depths. In the following discussion, it is assumed that the separation lengths are measures of the volume of recirculation regions.

**Effect of the position of the inlet slot**

FTCs were obtained in Tank B (L=2,5 m; W=0,9 m) for various H/s values. For practical reasons the position of the inlet slot was fixed at s= 0,1 m and the ratio H/s varied by changing the flow depth (H). The Reynolds number for all experiments was 2 000.

FTC characteristics for the s-pattern of flow (for H/s=1,1; 1,3 and 1,7) are plotted on the HED of Fig. 4, from which it is evident that by increasing the ratio H/s (the inlet slot approaches the mid-depth) the hydraulic efficiency deterioriates. This can be attributed mainly to the increased degree of short-circuiting, because the volume of the long (bottom) separation region increases and forces the tracer through a shorter route to the outlet, shifting the whole FTC to the left, thus resulting in decreased values of efficiency times. Furthermore, the intense (large-scale) mixing, which occurs in the recirculation region increases, as is also verified by the increased values of the mixing-dispersion characteristics (Fig. 4). The intense mixing results in a lower degree of plug flow. This behaviour suggests that for the s-pattern of flow to have a high hydraulic efficiency, the inlet slot should be located close to the surface. A similar behaviour was observed for the l-pattern, showing that the inlet-slot should be located far from the mid-depth, i.e. closer to the bottom. A further comparison was made to investigate the effect of the type of flow pattern (s or l) and to decide whether the slot should be located closer to the bottom or to the surface. The FTCs for the 2 bi-stable flow fields for the symmetrical case (H/s=2,0) were selected for this comparison and are shown in Fig.5. As depicted from Fig. 5, the FTC for the l-pattern is superior, because it is shifted to the right (having higher efficiency times) and it is less dispersed than the FTC of the s-pattern (showing that less mixing occurs in the smaller volume of recirculation region). A further indication of the lower degree of mixing is the higher value of $c_{max}$. This behaviour, which can be easily detected also from the HED of Fig. 6, suggests placing the inlet slot close to the bottom to create an l-pattern. This pattern resembles that formed by a denser influent, a case which was characterised by McCorquodale (1980) as beneficial for the efficiency of the settling tank, contrary to the case of lighter influent which creates a pattern similar to the s-pattern with severe short-circuiting problems. In practice, however, inlets are not placed near the bottom (Larsen, 1977) to avoid resuspension of solids, already deposited on the bottom of the tank.

**Effect of the use and position of inlet deflectors**

By placing deflectors in front of the inlet slot, the incoming flow is directed towards the bottom taking the pattern (d-pattern) of Fig. 2c. The recirculation region behind the deflector has a separation length of 4 depths, i.e. 50% of the long reattachment length, which would have been formed without deflector. This behaviour results in a significant reduction of short-circuiting, due to the longer path the tracer follows under the deflector and the reduction of mixing due to the smaller volume of the recirculation region. These results are clearly shown on the HED of Fig. 6.

The effect of the position of deflectors was studied in Tank B (L=1,89 m, W=0,395 m, s=0,065 m and R=1 500). Initially the deflector was placed 5cm far from the inlet wall and the reattachment length and the FTC were determined for various submersions of the deflector. The experiments have shown that for the deflector to be effective, its bottom edge must be placed at a lower level than the level of the inlet slot to effectively divert the incoming jet. By placing the deflector at a lower level, no noticeable change in the reattachment length or the FTC characteristics was observed. Experiments were repeated by placing the deflector 9 cm from the inlet wall and the results were similar. It can be concluded therefore that the position and submersion of the inlet deflector do not significantly affect the hydraulic efficiency of the tank provided that the position of the deflector is effective.

## Conclusions

FTCs were obtained in two model settling tanks and their characteristics were calculated and plotted on a diagram called the HED. Using the HED it was shown that the hydraulic efficiency increases, when the inlet slot is placed away from the mid-depth, either close to the surface or preferably close to the bottom. Experience has taught that placing the inlet slot close to the bottom should be avoided, in order to avoid high flow velocities and resuspension of deposited solids, thus forcing the design engineers to place the inlet slot near the surface creating the hydraulically not

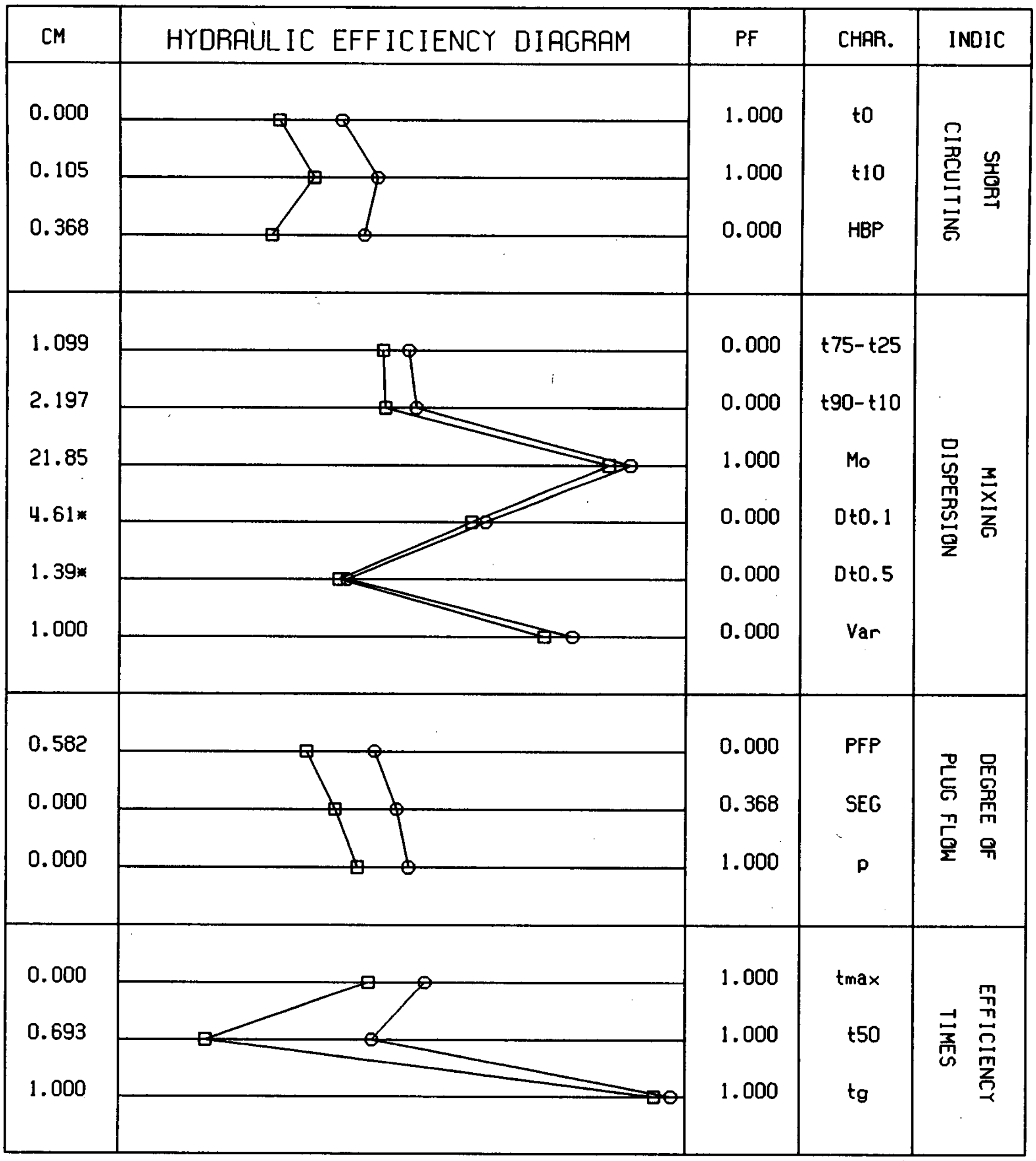


***Figure 6***
*HED for H/s=2,0 - Effect of flow pattern*
*s-pattern (□) - l-pattern (O)*

very efficient s-pattern of flow. In this case to avoid the formation of the s-pattern, inlet deflectors are used. The position of the inlet deflector (distance and submersion) is not very critical as long as the deflector remains effective and diverts the incoming jet towards the bottom. Again, the deflectors should not be submerged very deep to avoid high flow velocities close to the bottom.

The use of HED is not limited only for settling tanks. HED can be used for any reactor (e.g. aeration tank, chlorine chamber) whose hydraulic efficiency is to be determined.

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