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Evolutionary Design of the Inlet Structure of a High-Rate Stormwater Clarifier

BY:

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NATIONAL WATER RESEARCH INSTITUTE
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Cheng He[1], Jim Wood [2], Jiri Marsalek[3], and Quintin Rochfort[4]

Abstract

A computational fluid dynamics (CFD) model was used for redesigning a lamellar clarifier for high-rate stormwater treatment. Flow patterns in the clarifier were simulated using a volume of fluid (VOF) model and the simulated flow fields were analysed for various layouts of the inlet structure. The results showed that the hydraulic conditions in the clarifier could be improved by spreading the flow uniformly in both the horizontal and vertical directions, and reducing vertical circulation in the clarifier by attaching horizontal trailing baffles to the top edges of the inlet opening slots. Hydraulic improvements then resulted in better solids removal efficiency. Computer simulations and field data showed that compared to the original clarifier, the new inlet design produced two benefits: (a) improved flow conditions in the settling zone and (b) greatly reduced energy head losses increase the treatment capacity). In chemically aided clarification, the conventional clarifier with the new inlet design produced better suspended solids (SS) removal than the original conventional clarifier, even at a three times higher surface load rate. The field data also indicated that the SS removal efficiencies of the original clarifier with lamellar plates and the modified clarifier, without lamellas but with the new inlet design, were comparable. Thus, the main goal of this study, reducing maintenance (cleaning) costs of chemically aided high-rate clarification of stormwater by removing the lamellar plates, without a significant loss of settling performance, was achieved. Finally, it was noted that the numerical CFD model, compared with conventional methods of hydraulic clarifier design, was a flexible, powerful tool providing distinct advantages with respect to the speed, efficiency and reduced analysis costs, and a better understanding of the clarifier operation.

NWRI RESEARCH SUMMARY

Plain language title

Use of Computer modeling for redesign of a high-rate stormwater clarifier to improve the removal of suspended particles.

What is the problem and what do scientists already know about it?

The chemical addition in a clarifier with a lamellar plate pack has been found effective in high-rate treatment of stormwater by removing suspended solids. However, chemical addition makes the produced sludge sticky and the cleaning of plate undersides can be very laborious and costly. Also, the capacity and hydraulics condition in settling tank of the existing clarifier need to be improved to mitigate effects of the poorly designed inlet structure.

Why did NWRI do this study?

This study is a part of the government's efforts to develop technology for controlling wet-weather flow pollution along the Toronto Waterfront and thereby contribute to the delisting of this Area of Concern.

What were the results?

Computer simulations and field data showed that, compared to the original clarifier (with or without lamellar plates), the new inlet design has two advantages: (a) improved flow conditions in the settling zone inducing more effective settling, and (b) greatly reduced energy head losses. In chemically aided clarification, the conventional clarifier with the new inlet design produced better suspended solids (SS) removal than the original conventional clarifier, even at three times the surface loading rate. The field data also indicated that the TSS removal efficiencies of the original clarifier with lamellar plates and the clarifier without lamellas but with the new inlet design were comparable.

How will these results be used?

The results will be used by the City of Toronto in their Wet-Weather Flow Management Master Plan to the abate pollution along the Toronto Waterfront.

Who were our main partners in the study?

City of Toronto

Conception évolutive de la structure d'admission d'un clarificateur d'eaux de ruissellement à grand débit

Cheng He[1], Jim Wood [2], Jiri Marsalek[3] et Quintin Rochfort[4]

Résumé

Un modèle de dynamique des fluides numérique (DFN) a été utilisé pour modifier la structure d'un clarificateur lamellaire de traitement d'eaux de ruissellement à grand débit. L'écoulement dans le clarificateur a été simulé à l'aide d'un modèle de volume de fluide et les champs d'écoulement simulés ont été analysés pour diverses configurations de la structure d'entrée. Les résultats montrent que les conditions hydrauliques dans le clarificateur pourraient être améliorées en étalant l'écoulement uniformément tant sur l'horizontale que sur la verticale, et en réduisant la circulation verticale au moyen de déflecteurs de fuite horizontaux fixés au bord supérieur des fentes d'entrée, ce qui améliorerait l'efficacité d'extraction des solides. Des simulations sur ordinateur et des données recueillies sur le terrain ont montré que, comparativement au clarificateur initial, la nouvelle structure a deux avantages : a) des conditions d'écoulement améliorées à la zone de sédimentation et b) une forte réduction des pertes de charge, qui augmente la capacité de traitement. Dans la clarification assistée chimiquement, le clarificateur classique équipé de la nouvelle structure d'entrée éliminait mieux les solides en suspension (SS) que le clarificateur classique initial, même à un débit de charge de surface trois fois plus élevé. Des données recueillies sur le terrain ont également montré que les efficacités d'élimination des solides en suspension du clarificateur initial doté de plaques lamellaires et du clarificateur modifié, sans plaques lamellaires mais avec la nouvelle structure d'admission, étaient comparables. Par conséquent, le but principal de cette étude, qui est de réduire les coûts d'entretien (nettoyage) de la clarification à grand débit assistée chimiquement en éliminant les plaques lamellaires, sans perte significative de la performance de sédimentation, a été atteint. Finalement, on a constaté que, comparativement aux méthodes classiques de clarification hydraulique, le modèle DFN était un outil souple et puissant qui offre des avantages indiscutables concernant la vitesse, l'efficacité et les coûts d'analyse ainsi qu'une meilleure compréhension du fonctionnement du clarificateur.

Sommaire des recherches de l'INRE

Titre en langage clair

Utilisation de modèles numériques pour modifier la conception d'un clarificateur d'eaux de ruissellement à grand débit afin d'améliorer l'extraction des particules en suspension.

Quel est le problème et que savent les chercheurs à ce sujet?

L'addition d'agents chimiques dans un clarificateur doté d'un groupe de plaques lamellaires s'est révélée efficace dans le traitement à grand débit des eaux de ruissellement en éliminant les solides en suspension. Cependant, les agents chimiques rendent les boues collantes et le nettoyage du dessous des plaques peut être très laborieux et onéreux. De plus, il faut améliorer la capacité et les conditions hydrauliques de la cuve de sédimentation du clarificateur actuel pour atténuer les effets de la conception inappropriée de la structure d'admission.

Pourquoi l'INRE a-t-il effectué cette étude?

Cette étude fait partie des efforts du gouvernement pour élaborer des technologies visant à contrôler la pollution des ruissellements par temps pluvieux sur le secteur riverain de Toronto et, par conséquent, contribuer à éliminer cette préoccupation.

Quels sont les résultats?

Des simulations sur ordinateur et des données recueillies sur le terrain ont montré que, comparativement au clarificateur initial (avec ou sans plaques lamellaires), la nouvelle structure d'admission a deux avantages : a) des conditions d'écoulement améliorées dans la zone de sédimentation produisent une sédimentation plus efficace, et b) des pertes de charge fortement réduites. Dans la clarification assistée chimiquement, le clarificateur classique doté de la nouvelle structure d'admission extrayait les particules solides en suspension (SS) mieux que le clarificateur classique initial, même à trois fois le débit de charge de surface. Les données sur le terrain indiquaient également que les efficacités d'élimination des TSS du clarificateur initial avec plaques lamellaires et du clarificateur sans plaques lamellaires, mais doté de la nouvelle structure d'admission, étaient comparables.

Comment ces résultats seront-ils utilisés?

Ces résultants seront utilisés par la ville de Toronto dans son plan directeur pour la gestion des ruissellements par temps pluvieux afin de réduire la pollution dans le secteur riverain de Toronto.

Quels étaient nos principaux partenaires dans cette étude?

Ville de Toronto.

Evolutionary Design of the Inlet Structure of a High-Rate Stormwater Clarifier

Cheng He[1], Jim Wood [2], Jiri Marsalek[3], and Quintin Rochfort[4]

Abstract: A computational fluid dynamics (CFD) model was used for redesigning a lamellar clarifier for high-rate stormwater treatment. Flow patterns in the clarifier were simulated using a volume of fluid (VOF) model and the simulated flow fields were analysed for various layouts of the inlet structure. The results showed that the hydraulic conditions in the clarifier could be improved by spreading the flow uniformly in both the horizontal and vertical directions, and reducing vertical circulation in the clarifier by attaching horizontal trailing baffles to the top edges of the inlet opening slots. Hydraulic

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improvements then resulted in better solids removal efficiency. Computer simulations and field data showed that compared to the original clarifier, the new inlet design produced two benefits: (a) improved flow conditions in the settling zone and (b) greatly reduced energy head losses increase the treatment capacity). In chemically aided clarification, the conventional clarifier with the new inlet design produced better suspended solids (SS) removal than the original conventional clarifier, even at a three times higher surface load rate. The field data also indicated that the SS removal efficiencies of the original clarifier with lamellar plates and the modified clarifier, without lamellas but with the new inlet design, were comparable. Thus, the main goal of this study, reducing maintenance (cleaning) costs of chemically aided high-rate clarification of stormwater by removing the lamellar plates, without a significant loss of settling performance, was achieved. Finally, it was noted that the numerical CFD model, compared with conventional methods of hydraulic clarifier design, was a flexible, powerful tool providing distinct advantages with respect to the speed, efficiency and reduced analysis costs, and a better understanding of the clarifier operation.

Introduction

Settling is one of the most common unit processes applied in wastewater, combined sewer overflow (CSO) and stormwater treatment. In this process, separation of suspended solids (SS) is achieved in settling tanks (clarifiers), and this has been extensively studied for wastewater treatment applications (Krebs, 1991). There is a great wealth of information on the optimal design of wastewater clarifiers, addressing such issues as surface loading rates (SLRs) typically ranging from 1.4 to 2.5 m/h (Metcalf and Eddy, 2003), geometry of circular and rectangular clarifiers (Deininger et al., 1998; Zhou and McCorquodale, 1992), special clarifier structures including inlets, feedwells and baffles (Krebs et al., 1995; Ueberl and Hager, 1997), modes of operation with or without sludge return (Kinnear, 2000), and high-rate operation involving chemical additions and ballasted flocculation (Metcalf and Eddy, 2003).

The settling of stormwater differs from typical wastewater settling with respect to the lower concentrations of suspended solids (typically 100 mg/L – USEPA, 1983), high and variable SLRs of settling facilities (50 m/h or more), and the expected levels of suspended solids removal ranging from 60 to 80% (MOE, 2003). Consequently, only some of the information produced primarily for wastewater clarifiers can be applied in stormwater settling and further research is needed. In view of the low TSS concentrations, stormwater clarifiers behave similarly to primary clarifiers and the density effects typical for final clarifiers can be neglected (Krebs et al., 1998). The intermittent use of stormwater settling facilities imposes cost constraints on such facilities, which may be achievable with high-rate clarification techniques employing lamella plates or tube settlers and chemical addition.

Stormwater settling in various facilities was described extensively in the literature, as reviewed e.g., by Wood et al. (2005). However, the literature data are of limited help, because the clarifier performance for low SS concentrations without density effects are based on such factors as tank geometry; surface-loading rate; inlet, outlet and settling zone configurations; sludge collection; and incoming solids density and settling regime (Kinnear, 2000). These are typically not reported in the literature, because for most of these factors there is no simple way to describe them. Most of these factors were kept constant in the earlier phases of the study described here, and the TSS removals were reported as 5, 26 and 84%, for a conventional clarifier (SLR=15 m/h), a lamella clarifier (SLR=15 m/h), and a lamella clarifier with polymer addition at 4 mg/L (SLRs ranging from 10 to 36 m/h) (Wood et al. 2005).

While lamellar settling with polymer additions exceeded the target TSS removal (60-80%), there were concerns about laborious cleaning of lamellar plates after every storm event. To eliminate this expense, the lamella plates had to be removed while improving the clarifier hydraulics, in order to maintain the target TSS removal. Towards this end, clarifier modifications, which focused on the redesign of the inlet zone, were carried out in this study using a numerical model. The modified clarifier performance in SS removal was verified in two ways: (a) by computational fluid dynamics (CFD) simulations of velocity fields and particle transport for various clarifier configurations, and (b) by comparing the actual field performance of the modified and original clarifiers in SS removal. Such analyses served to verify the performance of a new inlet design and to demonstrate the usefulness of CFD modelling in (high-rate primary) clarifier design.

CLARIFIER STUDIED

The study partners, the City of Toronto, the National Water Research Institute (NWRI, Environment Canada) and the Ministry of the Environment (MOE) have been operating a pilot-scale demonstration project on high-rate stormwater clarification with a polymeric flocculant addition, which holds a promise of cost-effective mitigation of stormwater pollution (Wood et al., 2005). The main objective of this project was to evaluate an innovative compact treatment of stormwater flows and thereby support the implementation of the City of Toronto's Wet-Weather Flow Management Master Plan.

The focus of the stormwater treatment study was to evaluate the removal of suspended solids and associated pollutants by flocculant-aided clarification, under controlled experimental conditions. Constant flow rate experiments were conducted in a pilot-scale clarifier vessel with and without lamellar plates, and with and without varying dosages of a cationic polymer flocculant. At high surface loads, the cross-flow lamellar plates represented an essential component of the process apparatus. The total suspended solids (TSS) removal performance of the clarifier during the 2001 to 2003 operating seasons was encouraging (Wood et al., 2005), but with more than 50 stormwater events treated annually the cost and difficulty of cleaning the upper and lower surfaces of the lamellar plates was of concern. Therefore, the study team examined the feasibility of removing the lamellas, modifying the clarifier inlet structure, and evaluating the resulting flow patterns in the clarifier by numerical modeling.

The dimensions of the commercially supplied clarifier vessel are 3 x 1.4 x 2 m (length x width x depth) and its configuration is shown in Fig. 1. The clarifier vessel consists of three comparably sized zones. The original inlet zone was fitted with a series of horizontal louvers and vertical baffles designed to promote a uniform, low-turbulence flow field across the separation zone, which contained a removable lamellar plate pack. The outlet (withdrawal) zone, which was not changed in the new design, contains a skimmer plate for the retention of floating material. The relatively fast inflow enters the clarifier through two 100 mm diameter pipes and impacts the horizontal inlet deflector louvers. The function of these louvers is to reduce the inflow speed and disperse the flow by angled baffles (louvers) with small openings that can be seen in Fig. 1. The potential problem associated with this configuration is that flow direction distribution at the deflector exit is highly non-uniform and generates strong turbulence. However, at the same time this arrangement increases the energy head loss.

After flow passes through the inlet louvers, it enters the inflow energy dissipater, which is shown an enlarged detail in the upper left corner of Fig. 1. The dissipater consists of two rows of vertical baffles placed in two parallel vertical planes, 50 mm apart. The two rows of baffles are offset so that the downstream baffles block the flow passing through the slots between the upstream baffles. However, the flow exiting from the downstream baffles contains lateral velocity components disrupting flow conditions in the settling zone. The dissipater also causes a large head loss, which limits the hydraulic capacity of the clarifier. The maximum SLR in the original clarifier before reducing the height of the inlet energy dissipater was about 30 m/h, well below the proposed maximum experimental rate of 50 m/h. Unsatisfactory hydraulic conditions in the clarifier with respect to limited flow capacity, high turbulence and high velocity fluctuations were reported by Marsalek and Doede (1997), who measured 3D velocity distributions in the clarifier. These unfavourable hydraulic conditions were improved by using a removable lamellar plate pack, which is shown in Fig. 2.

The principle of suspended solids removal in lamellar plate clarifiers is well described in the literature (Metcalf and Eddy, 2003) and was further tested in the original clarifier, where the lamellar plates were found very effective in improving suspended solids removal (Wood et al., 2005). However, the original lamellar plate pack was not designed for easy cleaning of the lamellas when polymer flocculants are used. Polymer addition makes the produced sludge sticky and the cleaning of plate undersides is very labourious. Furthermore, the higher surface loading rates attainable with flocculants generate several times more sludge than unaided tests.

Hydraulic design considerations

High-rate clarifier design and particle separation considerations are a challenge because of high flow volumes and complex flow conditions, large hydraulic head loss, and fast flows with associated high turbulent energy in the particle separation zone. The inlet structure of a high-rate clarifier needs to dissipate the turbulent energy within a small space without sacrificing too much head loss and plays a very important role in determining the flow characteristics in the downstream particle separation zone.

In the conventional method (Metcalf and Eddy 2003) of settling tank design, the smallest settleable particle size under the expected flow rate is selected first, and then the corresponding settling (terminal) velocity v_c is calculated according to the particle physical properties from the Stokes law as

$$v_c = \frac{g(sg_p - 1)d_p^2}{18\upsilon} \qquad (1)$$

Where g, sg_p and d_p are the gravity acceleration constant, particle specific gravity, and diameter of the smallest settleable particle, respectively, and υ is the kinematic viscosity. The particle settling may occur in different flow regimes, laminar, transitional or turbulent, and adjustments of velocities calculated from equation (1), valid for laminar flow, may be required (Metcalf and Eddy, 2003).

Finally, based on the terminal velocity, the size of the settling tank can be estimated so that all particles with settling velocities equal to or greater than terminal velocity v_c will settle, and particles with settling velocities smaller than v_c either pass through the tank or will be partly removed. The terminal velocity, residence time (RT), and settling tank depth (D) are related as follows:

$$v_c = \frac{D}{RT} \qquad (2)$$

and RT can be estimated by the formula:

$$\mathrm{RT} = \frac{V}{Q} \qquad (3)$$

Where Q and V are the inflow rate and the tank volume, respectively. Equation (2) can be expressed in terms of the surface loading rate (SLR) by substituting Equation (3) for RT and assuming a rectangular tank, for which $V = D \bullet A$, where A is the surface area of the tank:

$$v_c = \frac{D}{\frac{V}{Q}} = \frac{Q}{A} = SLR \qquad (4)$$

Therefore, the surface area, A, can be easily obtained from above relationship after terminal velocity v_c and treated flow rate have been determined. However, equation (4) also states that the settling tank depth is unimportant in settling tank design, which is obviously not true in practice. The problem appears to be that in the estimation of the SLR, it is assumed that the entire flow passes through the settling tank along the tank surface. However, in the residence time calculation, it assumes that the active flow would occupy the whole tank volume. Obviously, neither assumption reflects reality and is questionable (Zhou and McCorquodale, 1992; Bretscher et al., 1992). Thus traditional design methods, which treat the various physical variables as simple averaged parameters without considering the hydrodynamic behavior of the fluid particle carrier are inadequate for producing an optimal clarifier design, especially, for particle removal at high flow rates with high turbulence.

Numerical Modeling Strategies

Models based on a mass-balance analysis are widely used to investigate bulk hydraulic flow characteristics and performance of primary and secondary clarifiers (Ott 1995; Dochain and Vanrolleghem 2001) since the flow speed and turbulence are usually small in those facilities. However, they are inadequate to diagnose detailed hydraulic conditions, turbulent intensity and other critical information needed to optimize the performance of different zones of a clarifier. Fluid-dynamic models (Kluck 1996; Krebs 1995; Pollert and Stransky 2003) have also been used to study various simple low SLR stormwater settling facilities. Most of them only focused on improving hydraulic conditions without further analyzing particle transport modeling.

In this study, commercially available CFD software was used to evaluate alternative clarifier designs by simulating flow conditions and particle transport in different structural configurations of the clarifier. The main objective of numerical simulations was to correct the observed problems in the original clarifier, rather than comparing the original and new designs. Therefore, simulation of hydraulic conditions in the original clarifier was not addressed in this study.

In order to calculate a 3-dimensional flow field, resolve the air and water interface, account for the hydraulic pressure effect on flow behaviour and simulate mass particle transport in a structure with complex geometry within a reasonable time frame, a two-stage approach was adopted by ignoring the interaction between the particles and their carrier. Thus, flow patterns were simulated first by means of a volume of fluid (VOF) model and subsequently formed a basis for simulating particle transport by the discrete phase (DP) model. This approach was found feasible by Adamson et al. (2003) for flows with low SS concentrations (< 1000 mg/L), which would be met in most practical situations.

After obtaining the flow field from the VOF model, the particle transport model was run on the basis of flow simulation data. The Lagrangian particle tracking method was used to track individual particle movement by calculating the balance of forces on the particle, which is written in a Lagrangian reference frame. Since this procedure includes more forces in the calculation of particle movement, it usually gives a better prediction of particle movement than the models using particle concentration changes to simulate the particle transport, but with higher computing times. The Lagrangian particle tracking approach assumes that the suspended particles are spherical and do not interact with each other. Even though the actual stormwater solids might not be discrete, or spherical, it was felt that this approach would still give good insight into the hydrodynamics of suspended solids inside the clarifier. Furthermore, since the focus of this study is to examine the particle removal rate for different inlet structures, it is not necessary to know the absolute particle removal rates for specific structural configurations. Therefore, the verification of simulated absolute particle removal rates using the particle tracking model was omitted. Also, in order to simulate flow behaviour and particle transport in realistic time, 30 minute simulations for real events were carried out for both flow hydrodynamic and particle tracking simulations. Such durations of simulations were sufficient to show the removal rate variations for different designs.

New Clarifier Inlet Zone Designs

In the original rectangular horizontal-flow clarifier (Fig. 1), the suspension enters at the upstream end and the treated water exits at the downstream end. The inlet flow structure must quickly generate a flow distribution that maximizes the opportunity for particles to settle. Therefore, the redesigning process started with modifying the internal inlet zone structure of the original clarifier. As stated earlier, the lamellar pack, one of which functions is to condition clarifier flow, was to be excluded in the new design. Therefore, it was essential that the new inlet zone structure provided maximum dissipation of kinetic energy and equalized the flow distribution over a minimum distance.

After many numerical simulations, three inlet designs with similar "U-shaped" structures (Figs. 3-5) were selected for more detailed studies. For all three proposed inlets, fast inflows exiting from three 0.075 m diameter pipes strike an impact baffle, which is 0.20 m downstream of the inlet pipe ports. The flow is forced downward through the entrance section of the duct, for about 0.9 m, and then it turns upward into the exit section of the duct through a bottom opening slot which is 0.25 m high. In the exit section, flow moves upward and this process should convert some turbulent kinetic energy into gravity potential energy. The exit duct has the same width as the entrance duct, 0.2 m (i.e., measured in the longitudinal direction), but the size of the bottom opening slot connecting the two duct sections is slightly larger than the width of the two side ducts to account for additional hydraulic resistance in the right-angle corner. In such an arrangement, the flow would travel at the same speed along the direction of the inlet structure with minimum lateral movement, which reduces the risk of generating turbulence. The structural differences among the three inlet designs were: (a) presence or absence of openings in the wall separating the inlet duct and the settling zone, and (b) configurations of the openings, which strongly influence flow conditions in the particle settling zone as described below.

In Design 1, there are no slot openings in the wall between the inlet duct and the settling zone (Fig. 3A), which is a common design feature of inlet structures used for releasing flow into the settling tank. One of the possible hydraulic advantages to this configuration is that there is little disturbance of the bottom sediment under low flow rates because the main flow stream is far from the vessel bottom. However, for high flows this reasoning may not be so plausible and has to be verified by numerical simulations. It can be seen from the simulated velocity pattern in Fig. 3B that without any openings in the separation wall, most of the flow passes directly through the clarifier in a very narrow surface layer. There are large recirculation zones in the clarifier, with poor hydraulic utilization of the clarifier volume, and this contributes to high flow velocities in the fast-flow surface layer.

Therefore, for most of the flow, the hydraulic residence time is short, which explains the low simulated particle capture rates indicated by cross symbols in Fig. 6.

Design 2 (Fig. 4A) features three horizontal slot openings spanning the full width of the clarifier. These slots were proposed on the basis of many numerical simulations discussed later. The height of each of the three slot openings is 0.10 m, the space between two adjacent slots is formed by solid vertical walls, 0.10 m high. The openings are used to distribute the inflow uniformly in the vertical direction, instead of allowing the entire flow to enter the particle settling zone at the top of the wall, which would utilize only a small cross-sectional area of the clarifier and result in high velocity flows and shorter residence times. The size of the slot openings has a large influence on flow distribution along the vertical axis and it is difficult to choose the "best" size, because of the sensitivity to the inflow rate. The 0.10 m opening was chosen as the final size on the basis of numerical simulations with SLRs of 50 m/h. The simulated velocity pattern showed that the region of the "active" flow in Design 2 becomes much larger than in Design 1, and this feature should reduce the flow speed and increase the particle settling rate. The simulated results on particle removal rates are shown in Fig. 6 as circle symbols, and indicate some improvement when compared to Design 1. However, a closer examination of the velocity pattern in Fig. 4B shows that the flows exiting from the three slot openings move upward, rather than longitudinally. This upward flow is undesirable, because (a) it reduces the thickness of the active flow layer, with most flow passing through the clarifier in the surface layer, and (b) it induces a strong, tank-scale vertical circulation due to the negative pressure generated from upwards moving flow in the vicinity of the inlet, which may disturb bottom sludge. In order to improve this flow pattern, a third set of simulations with modified opening slot configurations were carried out.

Design 3 (Fig. 5A) is similar to Design 2, but with horizontal trailing baffles added at the top of each slot opening to force the flow exiting the slots to travel in the horizontal direction. The length of these baffles in the horizontal direction, as used in simulations, was about 0.15 m (see Fig. 5A). When comparing the flow pattern in Fig. 4B (Design 2) to that in Fig. 5A (Design 3), a more uniform flow distribution becomes apparent in the latter case. The size and strength of the vertical eddy was reduced, which resulted in better particle removals presented as a solid line in Fig. 6.

To further improve flow conditions by directing flow in the longitudinal direction and suppressing lateral flow components, three vertical baffles were placed in the downward and upward inlet ducts, dividing them into four sub-channels. In such a configuration common to Designs 1-3, the turbulence associated with horizontal flow movement would be minimized.

In spite of the hydraulic improvements described above, even in Design 3, the flow distribution along the vertical axis is highly non-uniform, with only 50% of the total flow passing through the three slot openings and the remaining 50% over the top, for the simulated case with an inflow corresponding to SLR of 26 m/h, and even less (26%) for a larger SLR of 50 m/h. Forcing more flow through the horizontal slot openings should further reduce the longitudinal velocities in the clarifier and possibly improve the opportunity for particle settling. This could be achieved by extending the horizontal baffles (Design 3) upstream inside the duct. The length of such extensions would vary and increase from bottom to top. The optimal flow distribution among the three openings and the top for maximum particle removal is a complex issue and highly depends on the inflow rates and other factors, which will be discussed in another paper.

To further understand the particle removal performance for the three proposed inlet configurations, the flow residence time was calculated and used as a performance indicator. Obviously, the conventional calculation of clarifier residence time (volume/flow rate) yields the same residence time for all flow conditions and does not provide any meaningful information for further analysis. Since the particle settling zone was sub-divided into three similar narrower chambers, the hydraulic conditions among them would not be expected to vary much, and flow conditions in the middle chamber should be representative of those in the adjacent chambers. The velocity distributions along the clarifier longitudinal axis are shown in Figs. 7-9, indicating the vertical profiles in the settling zone near the inlet, in the centre and near the outlet, respectively. Fig. 7 displays the flow velocity profile near the inlet and shows that Design 1 produces the largest surface velocity (concentrated in the top 0.2 m surface layer) as indicated by cross symbols. As expected, in Design 3 (i.e., an inlet with three openings with horizontal trailing baffles), the active flow occupies a much larger portion of the flow depth with lower velocities represented by asterisk symbols in Fig 7. Design 2, designated by circular symbols in Figs. 7-9, shows an interesting feature occurring in front of the solid walls between the adjacent slot openings (their locations can be identified by zero velocities corresponding to the Design 3 curve) - the velocity is larger than that in front of the slot openings, which indicates a strong upwelling flow from an opening without a horizontal trailing baffle.

When flows reach the mid point of the clarifier length (after traveling about 0.4 m), the velocity profiles shown in Fig. 8 are similar to that near the inlet in the top half of the settling zone. A steep velocity gradient is observed for both Design 1 and Design 2, with maximum velocities much larger than in the case of Design 3. Strong opposite flows generated in Designs 1 and 2 indicate the presence of a strong vertical circulation. The maximum negative velocity near the bottom indicates that the vertical eddy extends all way to the sediment bed, which may potentially resuspend some of the settled particles. However, with the addition of trailing horizontal baffles (Design 3) the flow conditions were significantly improved, which can be documented by small variation in the velocity distribution curve with a much smaller range of velocities (Fig. 8) for all depths, and the absence of a large vertical eddy. When the flow reached the outlet after traveling another 0.4 m the velocity profiles maintained the same magnitude as that found at the mid point of the tank, except that the maximum velocities were reduced due to flow momentum dissipation, as seen in Fig. 9. Because of the scum baffle (or outlet tank wall), all velocity distribution curves indicate a flow direction reversal near the surface. The comparison of locations of the maximum negative velocities (along the vertical) for Designs 1 and 2 in Fig. 8 to those in Fig. 9, indicates that the maximum velocities in the latter case are found at lower depths, and this shows that the flow is at the edge of a large vertical eddy.

Fig. 10 shows the lateral distribution of longitudinal velocities at the mid-point of the tank. It is obvious that surface velocities in Design 3 are much smaller than those in the other two designs, because of the horizontal baffles on top of the openings forcing the flow to spread across a larger vertical space. Design 2 shows only a marginal surface flow velocity reduction compared to Design 1. Small lateral variations in flow velocities indicate that flows in the longitudinal plane of the each settling zone are relatively similar and uniform, which is favourable for particle settling.

Using the information in Figs. 7-9, the flow detention time can be estimated for the three different inlet structures. As a result of the complex flow patterns in the settling chamber, some simplifications have to be made before the detention time can be estimated. From Figs. 7-9 it can be seen that the vertical circulation exists in all the three designs. After this motion is established it may be reasonable to assume that the new inflow only provides the momentum to keep the circulation continuing without participating recirculation in the settling zone and negative velocity could be ignored in flow detention calculation. It can be approximated in Figs. 7-9 that the positive velocities occupy a space from the depth of 0.8m to water surface (1.6m) in all three locations for all three designs. The zero velocity point is about 0.8 m below the water surface, which is about the same depth as that of the lowest opening slot. Since the sections of all positive velocities are relatively linear, the detention time can be easily calculated by dividing the tank length by the averaged positive velocity. The calculated detention time is 23, 23 and 55 seconds for Designs 1, 2 and 3, respectively. It is not surprising to see that Design 1 and Design 2 have the same flow detention time since they share similar velocity profiles in the settling zone. With a minor modification of the inlet structure, consisting in adding the horizontal baffle on top of each opening slot, the flow detention time can be doubled. Such a modification is more efficient than doubling the tank length, because it also minimizes the vertical circulation generated by fast surface flow.

Having addressed the hydraulic flow conditions in the clarifier settling zone for each inlet structure design, the remaining concern for the U-shaped inlet was the conveyance of large particles which may accumulate in the inlet channel during clarifier operation. These materials would reduce the effective channel cross-section, and thereby increase hydraulic resistance and ultimately cause a partial blockage of the inlet channel. This problem had to be addressed before the proposed clarifier inlet design could be implemented in the pilot installation.

The pilot clarifier was fed directly with stormwater by a pump, without grit removal. In field operation, gravel, brick and concrete chips were transported into the clarifier. During field tests with inlet Design 3, debris particles accumulated on the bottom horizontal surface (see Fig. 5) because of dead flow zones in the compartment corners. The initial inlet design included a few circular holes in the bottom of the U shaped inlet channel for grit removal, which were blocked quickly and made cleaning the vessel at the end of a test difficult.

After many additional numerical simulations, the most promising and practical design for continuously transporting large particles (grit and gravel) out of the inlet channel was to use part of the available fluid flow energy for this purpose. The revised design featured a V-shaped floor, with a 35 mm slot opening in the centre, extending across the full vessel width (Fig. 11). In order to reduce simulation times, only the inlet section and a small portion of the settling zone were included in numerical simulations. Large grit particles were directed into the sludge zone via the bottom grit outlet of the inlet structure, and continued towards an inlet bottom wall, which prevented excessive flow from directly entering the settling zone and potentially stirring up settled sludge. Furthermore, an existing vertical baffle could be employed to prevent flow passing through the grit opening moving longitudinally into the vessel. This original vertical baffle was not extended to the tank bottom because the captured material was removed via a sludge wasting outlet situated at the upstream end of the clarifier. The size of the opening between the vertical baffle and floor of the clarifier is about 0.3 m which could be retrofitted with a sliding gate and closed if there is too much flow passing through during storm events. However, in field trials it was found that the bottom opening of this lateral tank wall became blocked by the accumulated sediment soon after the event started. The flow pattern in the inlet and part of the settling zone with the modified inlet structure is also shown in Fig 11 with 3-dimensional velocity vectors. Simulations at a flow rate of 60 L/s show that about 16% of total inflow passes through the inlet structure grit discharge slot.

Clarifier Performance in Stormwater Treatment

In a pilot-scale demonstration project of high-rate treatment of stormwater by clarification with a polymeric flocculant aid, the modified clarifier with the newly developed inlet structure (Design 3) was built and operated on line. In this project, suspended solids removals were measured under various inflow rates, polymer dosages and clarifier structure configurations during the past 4 years (Wood et al., 2005). The clarifier performance data discussed here focus just on the performance of the clarifier with the lamella pack and the modified clarifier with a redesigned inlet. Details of the pilot installation, stormwater characteristics and treatment results can be found elsewhere (Wood et al., 2005).

A comparison of chemically aided lamellar plate clarification, at a total vessel SLR of 35 m/h, and conventional clarification (without the lamellar plate pack) at a total vessel SLR of 43 m/h in the modified clarifier with the new inlet baffle system (Design 3) is presented in Fig. 12. Total suspended solids (TSS) concentrations are indicated for samples of the influent (raw stormwater) and polymer treated effluents of the lamellar and conventional clarification processes. Each curve represents cumulative frequency of non-exceedance for "n" grab samples (n is listed in the legend) collected during storm events at 10 minute intervals and analysed for TSS. All tests were conducted at a constant rate of inflow, in a steady state mode. Both the lamellar plate clarifier and conventional clarifier tests employed a polymer dosage of 4 mg/L. The lamellar plate clarification test series shown in Fig. 12 totalled 56 hours of operation during 11 stormwater events, while the conventional clarifier test series was operated for 49 hours during 13 stormwater events. Stormwater concentrations of TSS for the lamellar plate and conventional clarification tests were comparable during the test periods. The overall mean effluent TSS concentration of the lamellar test series was 57 mg/L while that of the conventional clarification effluent was 49 mg/L.

In the earlier conventional clarification tests (prior to the installation of the new clarifier inlet baffle system), seven tests conducted with the conventional clarifier at 4 mg/L polymer dosage and a total vessel surface load of 15 m/h, produced an average of 67% TSS removal (Wood et al., 2005). Thirteen tests completed in 2004 with the new clarifier inlet baffle system at a 4 mg/L polymer dosage were conducted at a total vessel surface load of 43 m/h and the average TSS removal efficiency was 77%. Thus the new design offers a 10 % improvement in TSS removal compared with the conventional clarifier even with a surface loading rate which was almost three times higher.

Conclusions

A CFD model was found to be an effective tool for the examination of alternative inlet structures for a high-rate clarifier. A VOF model was used to simulate flow patterns in the clarifier and the flow fields simulated for various inlet structures were analysed. To select the most favourable flow conditions for suspended particle removal among the various inlet configurations, a particle tracking model was applied to determine particle removal rates. The results showed that the hydraulic conditions in the original clarifier could be improved by spreading the flow in both the horizontal and vertical directions uniformly and reducing vertical circulation flow with the addition of horizontal trailing baffles on top of each flow opening slot. This resulted in better particle removal efficiency. Computer simulations and field data showed that, compared to the original clarifier (with or without lamellar plates), the new inlet design has two advantages: (a) improved flow conditions in the settling zone inducing more effective settling, and (b) greatly reduced energy head losses. In chemically aided clarification, the conventional clarifier with the new inlet design produced better suspended solids (SS) removal than the original conventional clarifier, even at three times the surface loading rate. The field data also indicated that the TSS removal efficiencies of the original clarifier with lamellar plates and the clarifier without lamellas but with the new inlet design were comparable. Thus, the main goal of this study, reducing maintenance costs by removing lamellas, but without sacrificing settling efficiency, has been achieved. Finally, the numerical CFD model, compared with conventional hydraulic design methods, was found to be a powerful tool providing distinct advantages with respect to the speed, efficiency and lower costs of analysis, and a better understanding of the clarifier operation.

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Notation

The following symbols are used in this paper:

Q = inflow rate;

A = tank surface area;

V = tank volume;

D = tank depth;

g = gravity acceleration constant;

sg_p = particle specific gravity;

d_p = smallest particle diameter;

υ = kinematic viscosity

v_c = terminal velocity.

References

Adamson A, Stovin V, Bergdahl L. (2003). Bed shear stress boundary condition for storage tank sedimentation. J. Environ. Eng. 129(7):651-658.

Bretscher, U., Krebs, P. and Hager, W.H. (1992). Improvement of flow in final settling tanks. J. Environ. Engng, 118(3): 307-321.

Deininger, A., Holthausen, E. and Wilderer, A. (1998). Velocity and solids distribution in circular secondary clarifiers: full scale measurement and numerical modeling. Water Res. 32: 2951-2958.

Dochain, D. and Vanrolleghem, 2001. "Dynamical Modeling and Estimation in Wastewater Treatment Processes." Published by IWA Publishing, Alliance HOUSE, 12 Caxton Street, London, UK.

Kinnear, D.J. (2000). Evaluating secondary clarifier capacity and performance. Proc. 2000 Florida Water Resources Conference, Tampa, Fl.

Kluck, J. (1996). "Design of Storm Water Settling Tanks for CSOs" 7th International Conference on Urban Storm Drainage Hannover, Germany.

Krebs, P. The hydraulics of final settling tanks. (1991). Wat. Sci. Tech., 23: 1037-1046.

Krebs, P. Success and shortcomings of clarifier modeling. (1995). Wat. Sci. Tech., 31(2): 181-191.

Krebs, P., Vischer, D. and Gujer W. (1995). "Inlet-Structure Design for Clarifiers." J. Envir. Engrg. 121(8) 558-564.

Krebs, P., Armbruster, M. and Rodi, W. (1998). Laboratory experiments of buoyancy-influenced flow in clarifiers. J. Hydraulic Res., 36(5): 831-851.

Marsalek, J. and Doede, D. (1997). Hydraulic assessment of the plate clarifier: flow capacity and outflow zone velocity field. NWRI technical Note AEPB-TN-97-002, National Water Research Institute, Burlington, Ontario.

Metcalf & Eddy, Inc., (2003). "Wastewater Engineering Treatment and Reuse", 4th ed., McGraw-Hill, New York, NY.

Ministry of the Environment (MOE) (2003). Stormwater management planning and design manual. MOE, Toronto, Ontario.

Ott, C. R., (1995). "Numerical Approach to Clarifier Operation According to Flux Theory." J. Envir. Engrg. 121(7) 544-545

Pollert, J. and Stransky, D. (2003). "Combination of computational techniques – evaluation of CSO efficiency for suspended solids separation." Water Sci. Technol., 47(4): 157-166.

Ueberl, J. and Hager, W. H., 1997. "Improved Design of Final Settling Tanks." J. Envir. Engrg. 123(3) 259-268

U.S. Environmental Protection Agency (EPA) (1983). Final report of the nation-wide urban runoff program, Vol. I. U.S. EPA, Washington, D.C., available from NTIS as PB84-185552.

Wood, J., He, C., Rochfort, Q. Marsalek, J., Seto, P., Yang, M., Chessie, P. and Kok, S. (2005), " High-rate Stormwater clarification with polymeric flocculant addition." Water Sci. Tech., 51(2): 79-88.

Zhou, S. and McCorquodale, J.A. (1992). Modeling of rectangular settling tanks. J. of Hydraulic Engng, 118(10): 1391-1405.

List of Figure Captions:

Fig. 9: Comparison of vertical profiles of horizontal velocities near the clarifier outlet for the three inlet designs studied.

Fig.10: Surface horizontal velocities across the clarifier in the middle of the particle settling zone for the three inlet designs studied.

Fig. 11: Proposed configuration of the redesigned inlet with an added gravel outlet and the simulated flow patterns.

Fig. 12: Lamellar and conventional clarifier performance, both with chemical additions (2003-2004 seasons).

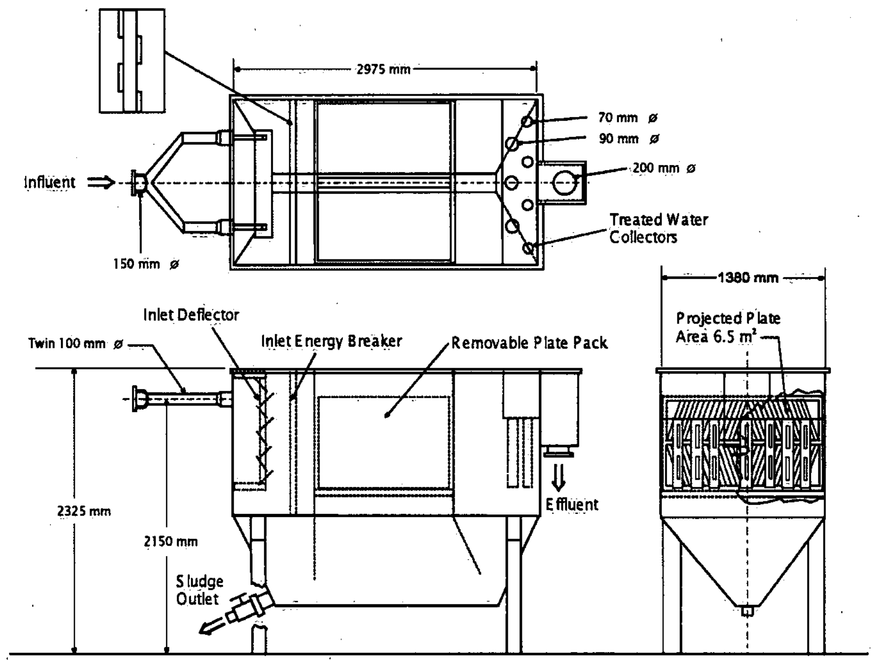
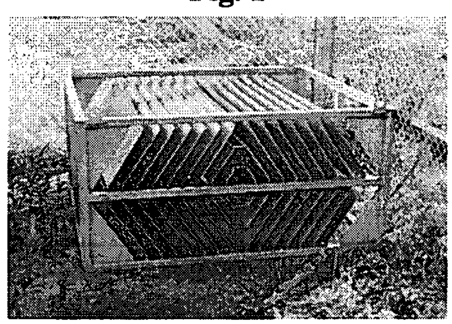


Fig. 1



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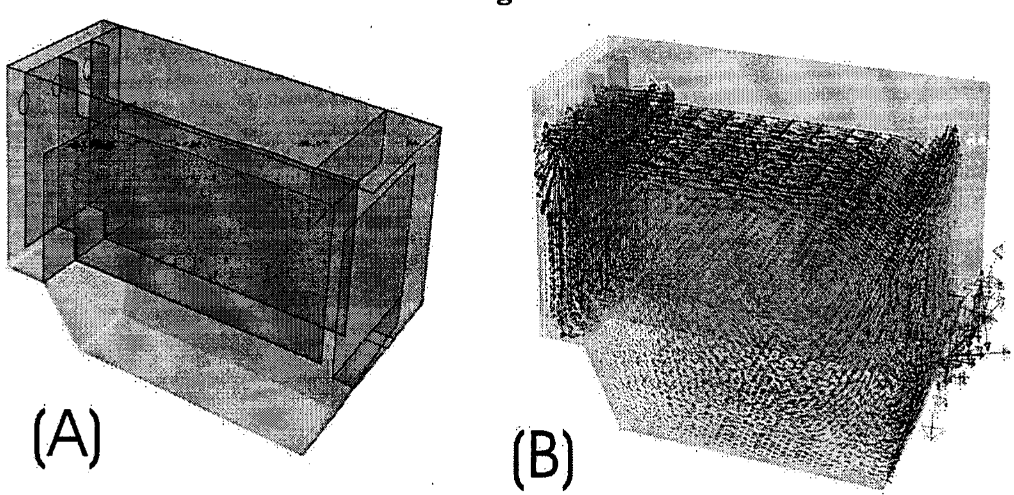

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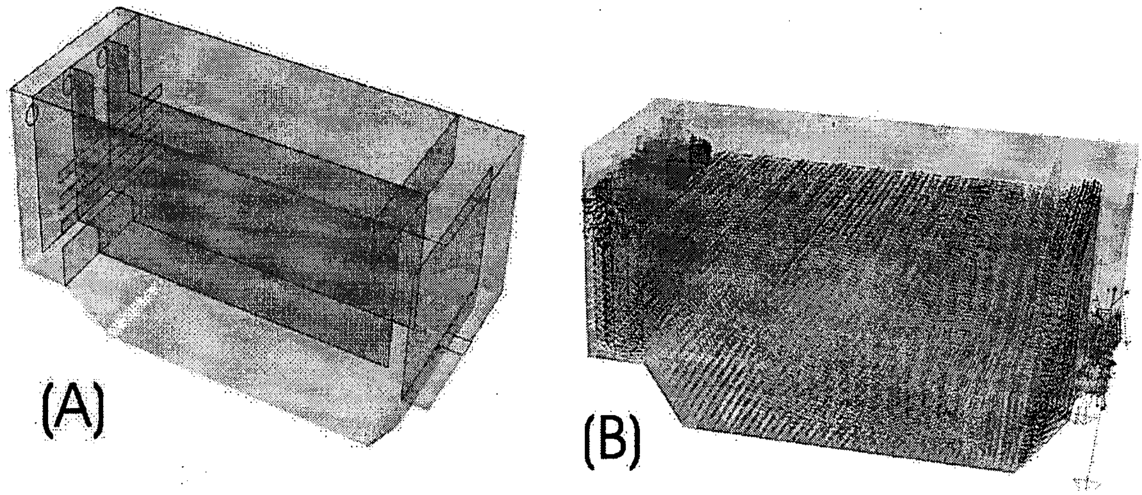

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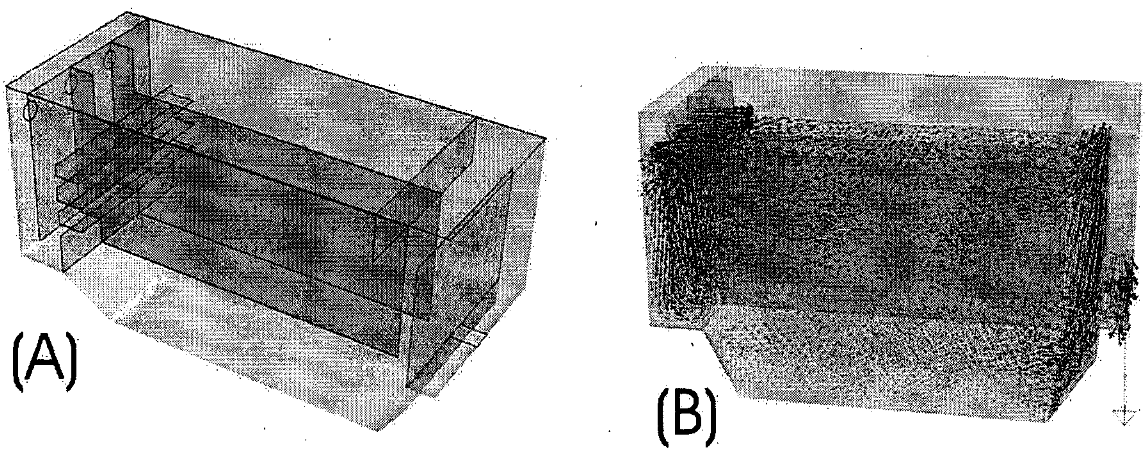

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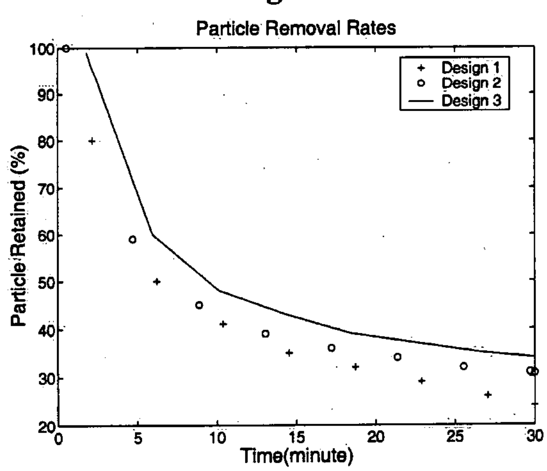

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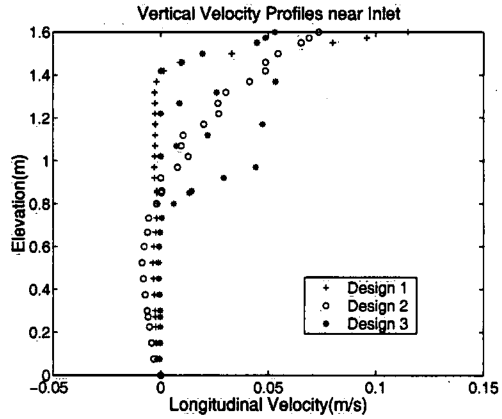

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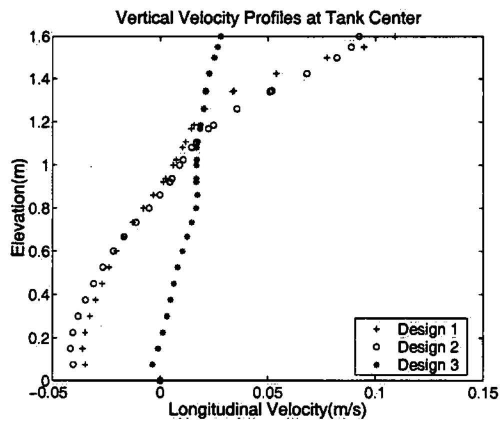

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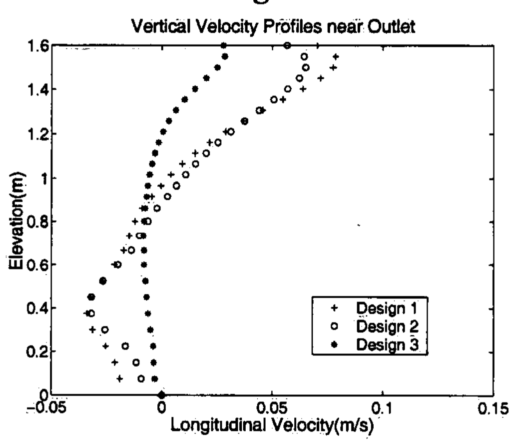


Fig. 9.

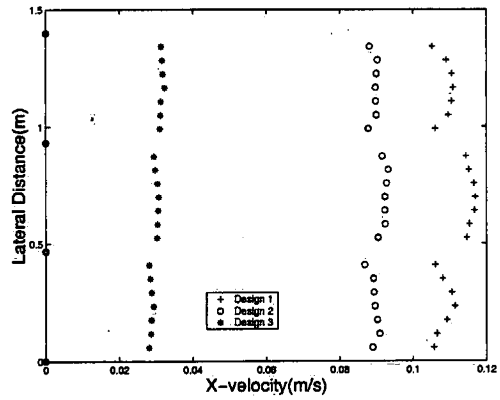
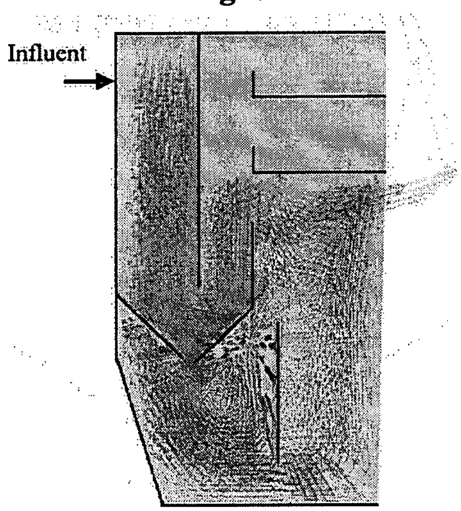


Fig.10



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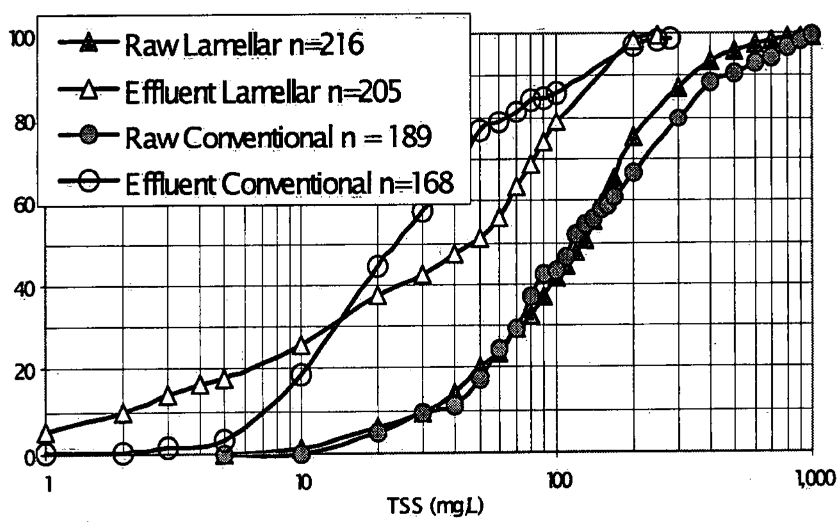

Fig. 12

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