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THE USE OF COMPUTATIONAL FLUID DYNAMICS FOR IMPROVING THE DESIGN AND OPERATION OF WATER AND WASTEWATER TREATMENT PLANTS

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SUMMARY

Computational Fluid Dynamics (CFD) studies of a secondary clarifier at Durban's Northern Wastewater Treatment Works, and of a clarifier at the potable water treatment plant at Umzinto, a small town near Durban, have been undertaken with a view to improving their load capacities. In both cases the units are located in relatively old treatment plants, which face continually increasing loads due to population growth. Increasing the capacity of existing equipment, rather than installing new equipment, constitutes an efficient use of development capital. Although the two clarifiers have considerable design differences, the CFD studies indicated remarkably similar circulating flows, which concentrate up-flow near the outer wall of the clarifier in the region of the clarified water overflow weirs. Baffles were designed to disrupt the circulation so as to distribute up-flow over a wider area, thereby reducing the maximum vertical velocities. In the case of the wastewater secondary clarifier, the modification has been implemented, and evaluated in comparative tests involving an otherwise identical unmodified clarifier. In the case of the potable water clarifier, the modification has still to be implemented. © 1999 IAWQ Published by Elsevier Science Ltd. All rights reserved

KEYWORDS

CFD; clarifier; computational fluid dynamics; potable water; process intensification; wastewater.

INTRODUCTION

The provision of water and sanitation services in many parts of South Africa is under great pressure as a result of population growth and rapid urbanisation. There is a drive to accommodate a large sector of the population which previously did not have access to such services. However, this campaign has to compete for limited development capital with many other national priorities. Conventional water and wastewater treatment plants are designed for fairly long operational lives, and, in a situation where demand is growing steadily, this implies that there will be a substantial period where the investment in a new facility will be under-utilised. It is thus important to ensure that existing plant operates as efficiently as possible, in order to delay new investment.

The efficiencies of processes carried out in very large vessels, as are typical of water and wastewater treatment plants, are often limited by non-uniform, non-ideal flow characteristics. Thus, clarifiers generally operate at loadings substantially less than their nominal surface areas and the settling rate of solids would suggest. Various researchers have used CFD modelling to investigate methods of improving the design and operation of clarifiers (Krebs, 1991; Bretscher *et al.*, 1992; McCorquodale and Zhou, 1993, 1994; Krebs *et al.*, 1992, 1995). A general conclusion, shared by all these authors, is that flow non-idealities in clarifiers are usually associated with circulating flows generated by excess energy in the feed. This has two main sources: the kinetic energy associated with the inlet flow velocity, and the gravitational potential energy associated with the higher concentration of solids in the feed relative to the clarified water in the vessel. In these papers the question of modifying an existing unit, as opposed to designing a new one, has received less attention. It is well known that the capacity of a sedimentation basin can be increased substantially by filling its volume with tilted tubes or tilted plates. Such *high-rate* settlers may have overflow rates up to twice those of conventional settlers, and furthermore are less affected by overloads (Yao, 1973). However, filling the entire space with baffles in this way constitutes an expensive modification in itself, and is often not compatible with the design of the sludge removal system on a particular clarifier.

CFD modelling techniques offer the possibility of designing baffle systems to improve the flow characteristics of a clarifier in such a way that optimal placing achieves the maximum benefit for the minimum amount of physical hardware to be installed. The two case studies described in this paper confirm the value of this idea. Although it cannot be claimed that the designs involved are truly optimal, or that the projected improvements have been demonstrated to be fully realised in practice, the improved capacities were achieved by remarkably small modifications, and were at least qualitatively demonstrated in the one case which has been implemented.

CASE 1: A SECONDARY WASTEWATER CLARIFIER

Introduction

The secondary clarifiers at Durban's Northern Wastewater Treatment Works suffer from carry-over of solids during periods of high load, particularly after heavy rains. The wastewater treatment works is faced with a continually increasing load, and any increase in the capacity of its existing equipment will postpone the installation of new capacity.

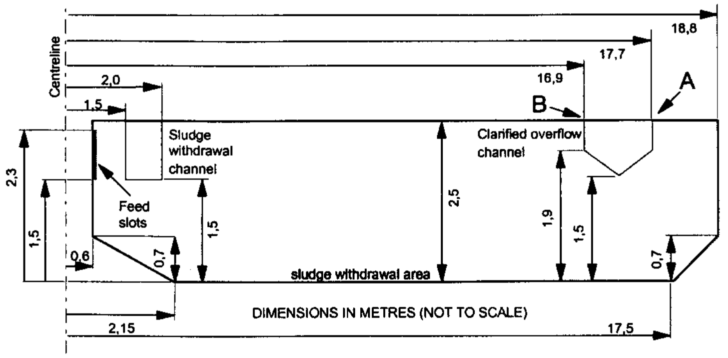


Figure 1. Sectional diagram of a secondary clarifier at Northern Wastewater Treatment Works.

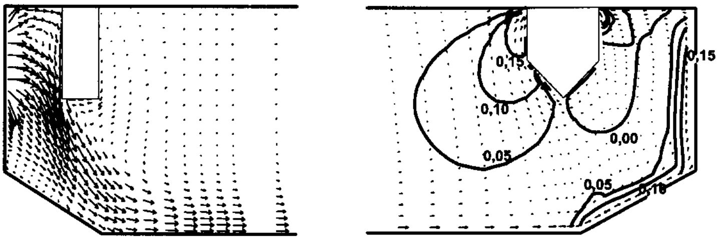
The clarifier is fed with mixed liquor from the activated sludge plant via a series of rectangular slots in a central concrete pillar. Sludge is picked up by hydrostatic head from the floor of the clarifier by a set of eight vertical upflow pipes attached to a radial bridge which revolves once every 30 minutes. The clarified water is collected in a circular channel set 1 m in from the outer wall, with notched weirs on the outer and inner sides (A and B in Figure 1). At 2.5 m deep, these clarifiers are unusually shallow for such units, which means that their capacity to accumulate sludge during overload conditions is smaller than usual.

In wet weather when heavy concentrations of sludge were carried over the weirs, it was notable that this occurred mainly at the outer weir (A in Figure 1).

The CFD Model

The clarifier is cylindrically symmetrical, apart from the revolving sludge withdrawal mechanism. To model this realistically constituted a major difficulty, as it not only broke the symmetry, turning what would otherwise be a two-dimensional problem into a three-dimensional one, but also introduced a cyclically moving boundary condition. The other feature which would have introduced severe complications would be realistic modelling of the sludge as it settles and concentrates in the clarifier. These complexities were neglected, in the hope that a simplified model would prove adequate. Consequently, the system was modelled as a steady-state, two-dimensional, cylindrically symmetrical problem, involving pure water only. The sludge withdrawal was represented by distributing the time averaged flow uniformly over the 360° traversed by the bridge. Although this constitutes a drastic simplification of the boundary condition, it was hoped that the flow distribution in the region of the weirs would still be adequately represented.

Flow rates to be used in the model were determined from measurements conducted on the clarifier on a day after heavy rains. The overflow stream is not metered, so the flows over the weirs were estimated by measuring individual rates through a sample of 73 out of the 689 weir notches, using a measuring cylinder and stopwatch. This yielded flow estimates of 0.166 m^3/s over the inner weir, and 0.073 m^3/s over the outer weir. The total of 0.239 m^3/s was just less than the maximum wet-weather overload (0.246 m^3/s) quoted in the design specification for the unit. The underflow was metered at 0.109 m^3/s.



Contours of vertical velocity in m/min

Figure 2. CFD simulation of the unmodified clarifier under high load conditions on 19 June 1995.

The most notable feature of the simulation was the presence of a circulating flow within the clarifier, causing the highest vertical up-flow velocity components to occur in the vicinity of the outer wall. Similar results have been repeatly reported in other studies (e.g. Bretscher *et al.*, 1992; Krebs *et al*, 1992) The effect here is due to the geometrical relationship between the inlet, the reaction baffle and the clarified water outlet. In reality, the higher density of the feed, compared to the bulk of the clarified water, has the effect of enhancing this circulation, though the contribution of this phenomenon is less marked under high flow conditions (McCorquodale and Zhou, 1994).

The significance of the vertical upwards velocity contours plotted in Figure 3 may be judged by comparison with the sludge settling velocities observed during the test. Values of between 0.02 and 0.03 m/min were measured, depending on the size of the flocs. The rate of settling is also a function of the sludge concentration, but this relationship was not investigated. These values were taken to be representative of the sludge which just reached the weirs under the prevailing conditions, and were about one third of the corresponding simulated up-flow velocities.

Design of a baffle using CFD modelling

On the premise that the clarifier's performance was being limited by the maldistribution of up-flow resulting from the circulation indicated by the model, a series of simulations was undertaken to find a means of reducing the circulation and the vertical velocities in the vicinity of the weirs.

The configuration eventually chosen placed a 280 mm high cylindrical baffle at a radius of 2.5 m. Figure 3 shows the model results for the clarifier fitted with a baffle, corresponding to Figure 2 for the unmodified clarifier, with the same inlet and outlet boundary conditions as before. The prediction exhibits greatly reduced upflow velocities in the vicinity of the weir, bringing them close to the values measured for the settling velocities of the sludge. The concept is similar to the dividing wall described by Krebs (1991), however, by locating it close to the inlet, the energy dissipation is acheived with a very compact structure, which furthermore did not require extensive modification of the revolving sludge collection mechanism.

In view of the simplicity and relatively low cost of the baffle, it was decided to make the modification to one of the four clarifiers at the works on a trial basis. The baffle was constructed from fibreglass, and mounted on stainless-steel brackets bolted to the clarifier floor.

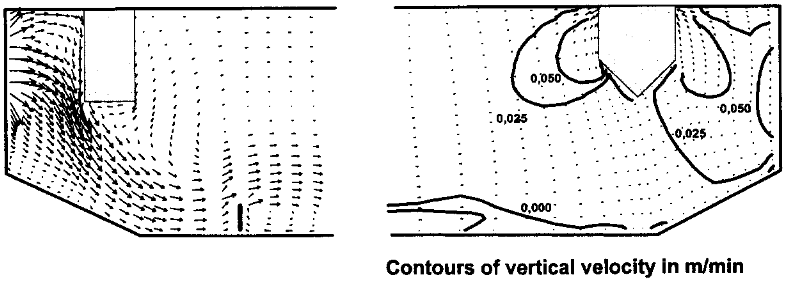


Figure 3. CFD simulation of modified clarifier under high load conditions.

Evaluation tests

Under normal load conditions, the presence of the baffle has little effect on the performance of the clarifier. In order to judge whether the baffle was effective it was necessary to evaluate it under high-load conditions. The measurement and control facilities at the wastewater works provided little opportunity for conducting carefully controlled experiments. Two flow meters were available to measure underflow rates (among the four clarifiers), and the inflow to the plant was metered. Only underflow rates could be manually adjusted, all the other flows were uncontrollable. By running only two clarifiers, it was possible to both subject them to a temporary overload during the daily surge of flow to the works between 6:30 and 10:30 am, and to set the underflows to be the same, using the two meters. This allowed a direct comparison to be made between the modified clarifier and an unmodified clarifier, under nearly identical, though not very well defined, conditions. Two such tests were undertaken, the first on the 22nd of January, and the second on the 6th of February 1997.

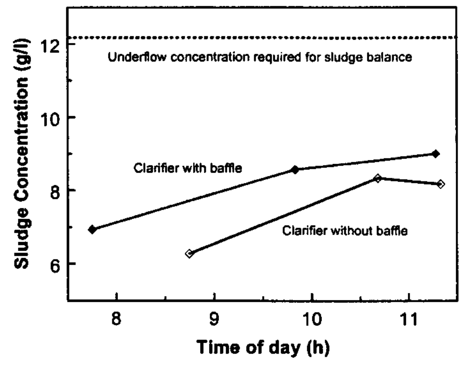


Figure 4. Underflow sludge concentrations measured during the 1st test on 22nd January 1997

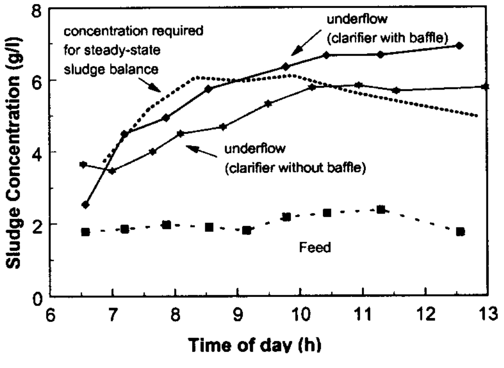


Figure 5. Underflow sludge concentrations measured during the 2nd test on 6th February 1997

The flow to each individual clarifier could not be measured: the total flow was presumed to be equally distributed between the two by the symmetrical splitter box. The underflow rates were set to 330 m^3/h on each clarifier. The feed concentration remained almost constant during the duration of the test, at 3 g/l, while the underflow concentrations increased gradually as the sludge level in the clarifiers rose (see Figure 4).

The most significant features of these results were that the sludge balance indicated that the inventory in the clarifiers was increasing throughout the test, showing that both clarifiers were definitely overloaded; and that the clarifier fitted with the baffle consistently achieved a higher underflow concentration than the unmodified unit, which implied that the modified unit was accumulating sludge less rapidly. Visual impressions of the clarifiers appeared to confirm this: the clarified water from the baffled unit was appreciably clearer throughout the test, and towards the end of the test (at about 11:10 am) sludge started to flow over the weir of the un-baffled clarifier at a few isolated points around its perimeter. At this stage the inflow was already declining, and the condition did not develop into a full-blown failure. The modified clarifier, on the other hand, showed no signs of imminent failure at any stage.

Based on the experience of the first test, it was decided, for the second test, to increase the underflows to 390 m^3/h. As it happened, the clarifier feed had a lower sludge concentration (2 g/l) than during the previous test. It is evident, from the underflow concentration required for sludge balance (i.e. the concentration required to keep the sludge inventory constant with the existing flow rates) in Figure 5, that, as a result of the lower sludge concentration in the feed, together with the higher underflow rates, the clarifiers were not seriously overloaded, and both managed to achieve a balance between sludge inflow and outflow during the test period. Nevertheless, as on the previous occasion, the clarifier with the baffle consistently achieved a higher sludge concentration in the underflow than the un-baffled clarifier, and came to balance approximately 1.5 hours earlier, when the inflow was at its peak. The latter did not manage to do this until after the peak flow had passed.

Conclusions

The tests on the two clarifiers have demonstrated that, with the baffle installed, the clarifier achieved a higher underflow sludge concentration under high-load conditions. This enabled it to handle a more intense, or a more prolonged overload, without heavy carry-over of sludge. During the course of the tests, it became evident that the capacity of the clarifier was affected by a number of other factors, such as the concentration of sludge in the feed, the settling characteristics of the sludge, the underflow rate, the duration of the overload condition, and the initial amount of sludge in the clarifier. It also seemed that the baffle might not provide any significant benefit when the degree of overloading was very high. In view of these complications, it is not possible to provide a simple statement of the degree to which this capacity has been improved.

CASE 2: THE POTABLE WATER CLARIFIER AT UMZINTO

Introduction

The Umzinto waterworks has 3 circular clarifiers of similar design. The water requirement of the area (a small coastal village) is very seasonal, with a strong increase in demand over the December-January holiday period, during which the clarifiers appear to have insufficient capacity. It is anticipated that the works will only be in operation for a few more years, so that a large investment in additional capacity is difficult to justify. It would therefore be most desirable if an inexpensive means could be found to increase the capacity of the existing units.

The clarifier consists of a central flocculation section, and an outer settling section, separated by a concrete skirt which extends down from the surface, as shown in Figure 6. The feed to the clarifier is introduced via a vertical pipe which comes in from the floor at the centreline, and discharges into a venturi device which serves to mix the incoming stream with already flocculated slurry, inducing a circulating flow in the flocculation section. The clarified water flows over a weir into the launder which is located at the outer wall. The sludge which settles on the sloping floor is moved to the central pit by a scraper driven by a revolving bridge. The sludge withdrawal occurs intermittently at the bottom of the central pit, and constitutes a very small proportion of the total flow.

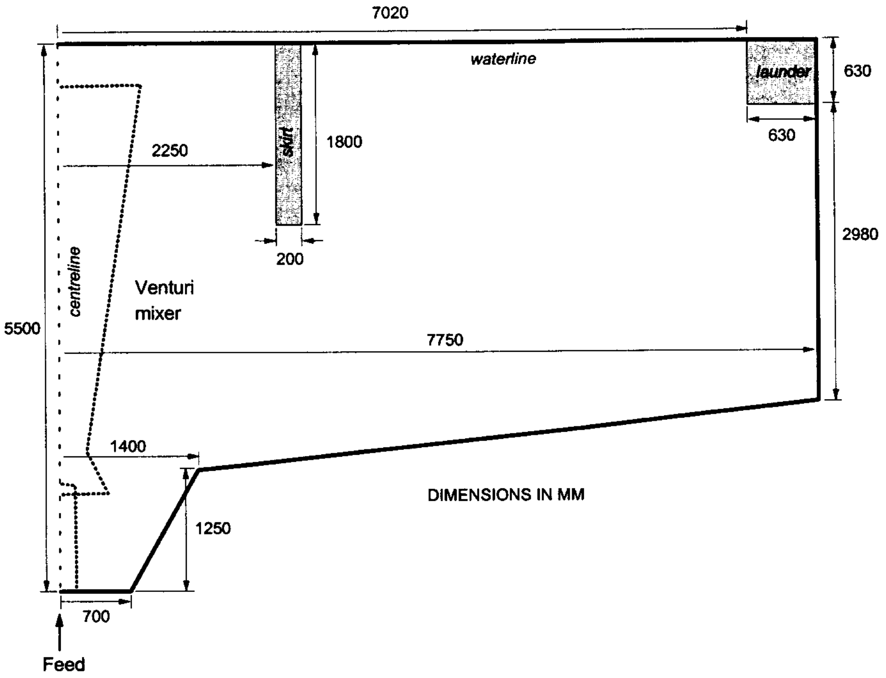


Figure 6. Half-sectional diagram of the structure of the Umzinto clarifier

Modelling basis and assumptions

The design overflow rate of the clarifier was stated as 1,4 m/h, which is fairly typical of a conventional sedimentation tank. This was taken to be related to the annular area between the skirt and the outer wall (1.4 m/h x 169.8 m^2 = 238 m^3/h). This volumetric flow rate was specified as a withdrawal at the weir location. The feed pipe opening was specified as a fixed pressure region, where the flow rate was allowed to satisfy the material balance. The sludge withdrawal was omitted from the model, as it occurred intermittently at long intervals, and would have a minimal influence on the flow patterns in the vicinity of the weirs. No modelling of the settling behaviour of the sludge was included. In view of these approximations, the model could not be expected to be a completely accurate representation of all details of the actual clarifier behaviour. In particular, there was a potential problem in judging the efficacy of any modelled modification to the clarifier, in that the ultimate criterion must be based on the settling behaviour of the sludge, which was not explicitly present in the model at all. The following argument was used to evaluate all model results:

It was assumed that the critical feature of the flow patterns was the distribution of vertical up-flow velocities crossing the annular plane extending horizontally from the bottom of the skirt to the outer wall (shown as the line AB in Figure 7). Any solids which reach the weir must be carried across this plane by a liquid flowing upwards at a greater velocity than the sludge settling velocity. No data were available for the sludge settling velocity, but it was assumed that the clarifier would operate satisfactorily at its nominal maximum rate of 238 m^3/h. Thus, a model of the unmodified clarifier operating at this rate was solved to provide a vertical velocity profile over the critical cross-section which would serve as a basis of comparison for all subsequent models. For these it was assumed that, if the maximum vertical velocity across the critical cross-section did not exceed that of the base-case model (0,11 cm/s), the corresponding operation of the clarifier would be satisfactory. Thus, the model results which follow should not be judged on an absolute basis, but only relative to the base-case model, which is illustrated in Figure 7. The velocity vectors in the flocculation section of the clarifier have been omitted from the diagram, as the velocities there are very much higher than in the settling section, and cause the diagram to become confusing.

Proposed modifications

Considering the difference in configuration between this clarifier and the Northern's clarifier, it was remarkable how similar the circulation pattern was predicted to be. A baffle in a position similar to the previous one suggested itself, and, indeed was found to increase the predicted overflow rate to 298 m^3/h for a maximum upflow velocity of 0,11 cm/s on the critical cross section, an improvement of 25 %. However, in this case, a baffle in this position would have interfered with the revolving sludge scraper, which would have required expensive modification. Consequently, a different solution was sought. It was noticed that, in this case, the circulation was driven by the combination of a downward velocity at the concrete skirt separating the flocculation section from the settling section, and an upward velocity at the outer wall, due to the withdrawal of clarified water at the top corner.

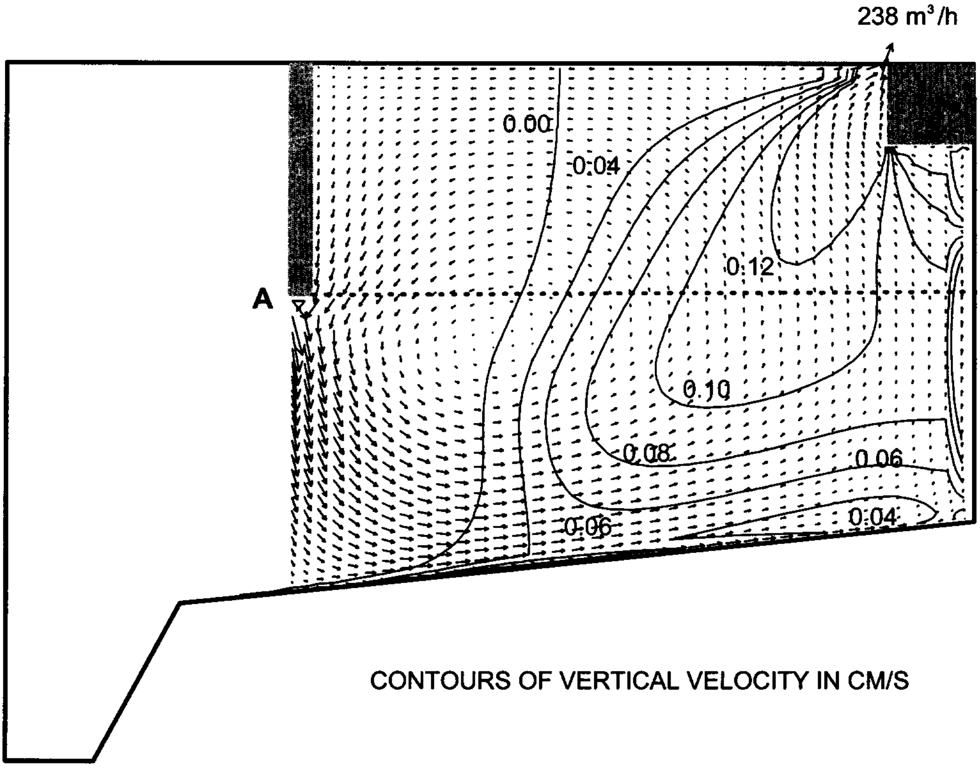


Figure 7. Simulation of the existing clarifier under conditions of maximum design load.

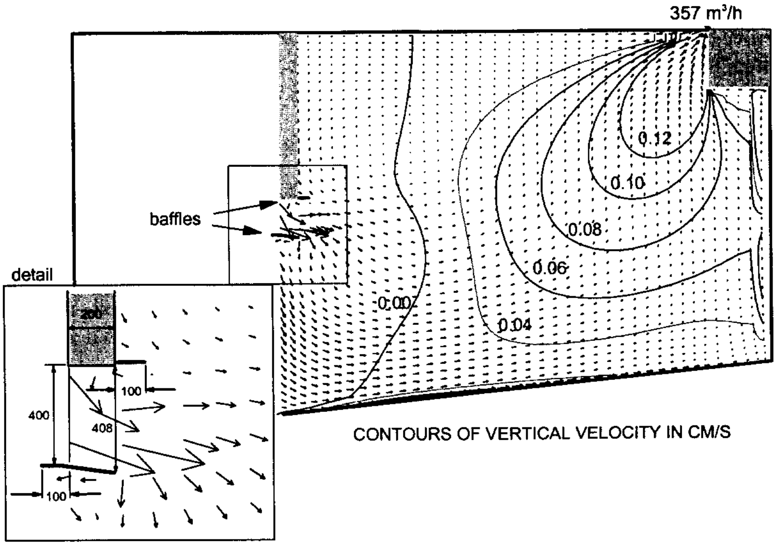


Figure 8. Simulation of the clarifier modified with 2 baffles mounted on the skirt.

This suggested suspending a small baffle from the concrete skirt to direct some of the downward flow at that point into the settling section (see Figure 8). By angling the baffle slightly downwards (just 2,3° from the horizontal) it was possible to almost cancel the circulation in the settling section. This arrangement was predicted to give the same predicted improvement of 25% increase in loading for the same maximum up-flow velocity across the critical plane. Adding another small baffle to the outside of the skirt, as shown, reduced the circulation still further, resulting in another 25% improvement.

Conclusions

It remains to be seen to what extent the predicted improvements can be realised in practice, as the proposed modifications have not yet been implemented. The remarkably small size of the proposed baffles means, that the cost will be small enough to try it, even if it proves less successful than predicted.

OVERALL CONCLUSIONS

These case studies re-confirm the importance of limiting the secondary circulations in clarifiers to achieve greater solids separation efficiency. Studies in the literature have proposed a number of ways of achieving this objective: it is clear that many possible solutions are technically valid, and the best in a particular case will depend on local circumstances. CFD modelling techniques, which are rapidly becoming more and more accessible to practising engineers, should allow a designer to balance flow-related inefficiencies against equipment cost in a rational way. CFD techniques are been used increasingly for the design of new equipment: the examples presented here indicate that substantial improvements, at very modest expense, may be possible on older plants which were designed without the aid of such methods. The studies reported here used only the most basic flow modelling, however CFD codes are capable of simultaneous modelling of flow with other processes, such as heat transfer, chemical reaction and phase separation, and it can be expected that future equipment designs will become more compact and efficient.

ACKNOWLEDGEMENTS

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