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# An approach to improve the separation of solid–liquid suspensions in inclined plate settlers: CFD simulation and experimental validation

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ABSTRACT

The most important requirements for achieving effective separation conditions in inclined plate settler (IPS) are its hydraulic performance and the equal distribution of suspensions between settler channels, both of which depend on the inlet configuration. In this study, three different inlet structures were used to explore the effect of feeding a bench scale IPS via a nozzle distributor on its hydraulic performance and separation efficiency. Experimental and Computational Fluid Dynamic (CFD) analyses were carried out to evaluate the hydraulic characteristics of the IPS. Comparing the experimental results with the predicted results by CFD simulation implies that the CFD software can play a useful role in studying the hydraulic performance of the IPS by employing residence time distribution (RTD) curves. The results also show that the use of a nozzle distributor can significantly enhance the hydraulic performance of the IPS, which contributes to the improvement of its separation efficiency.



## 1. Introduction

A gravity settler is a common unit with wide applications in the treatment of water, domestic wastewater and industrial wastewater. Solid–liquid separation efficiency of this type is directly related to the surface area available for settling, but under limited space conditions – as in industrial wastewater treatment – the use of an inclined plate settler (IPS) is preferred. It provides high space–time yield due to the short settling distance, and the available settling area is dependant on the total area of the plates projected on a horizontal surface.

Separation efficiency of IPS is usually well below the theoretical performance due to many factors. Okoth et al. (2008) summarised these factors by the modelling of suspension–sediment interaction phenomenologically. In their experimental study, they employed a nozzle distributor to improve the hydraulic performance of IPS which is one of the factors affecting the separation efficiency. However, they did not investigate in detail the effect of using this nozzle on both distribution of the total flow between the settler channels and flow patterns of the entire IPS system, both of which have a significant impact on the separation performance of the IPS. The equalized distribution of suspension within each settler is important to obtain an equal overflow velocity on every plate, which contributes to the improvement of the IPS efficiency, while the flow patterns are essential in determining the flow characteristics in order to achieve a reliable design (López et al., 2008).

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To explore operational shortcoming and characterize new separation equipment, it is important to understand the reactor hydrodynamics, which may be achieved by interpreting the reactor residence time distribution (RTD) (Behin and Aghajari, 2008). The residence time distribution of a reactor is one of the most informative characterizations of the flow pattern in a reactor (Gavrilescu and Tudose, 1999). Knowledge of the liquid RTD is important for a number of reasons, such as allowing for accurate modelling of the system and aiding in reactor design to achieve or preserve a desired flow pattern (Behin and Aghajari, 2008).

The flow in tanks always deviates from the ideal plug flow or complete mixed flow and is usually described as a non-ideal flow pattern. Levenspiel (1999) described two methods for the characterization of a non-ideal flow pattern. One is the longitudinal dispersion (LD) model which represents a flow that deviates from plug flow, and the other is the tanks in series (TIS) model which describes the mixing within a single real reactor as a number of equally sized continuous stirred-tank reactors in series (CSTRs). When the number of tanks in series is one, the model predicts the performance of an ideal CSTR. As the number of tanks in the TIS model increases, the flow within the reactor approaches that of a plug flow reactor (PFR) (Bircumshaw et al., 2006). Both the LD and TIS models are characterised by dispersion number and the number of tanks in series (NTIS) respectively. The TIS model was used in this study because it is mathematically much simpler than the LD model. Also, the NTIS does not depend on the definition of the inlet and exit boundary conditions.

Computational fluid dynamics (CFD) has become a powerful tool in the reactor design process and provides useful and detailed information prevailing in the reactors, such as velocity field, concentration distribution, and phase hold-up distribution (Zhang et al., 2007). CFD is typically used in the simulation of RTD (Patwardhan, 2001; Choi et al., 2004; Moullec et al., 2008; Aubin et al., 2009). CFD codes used in software package such as Fluent, CFX and Cosmos offer different models for numerical solution of Navier Stokes partial differential equations. Generally, the model should be experimentally verified (Thýn et al., 2002).

Two turbulent models ($k-\epsilon$ model and $k-\omega$ model) were implemented in the present study to predict both velocity flow field and RTD curve. Thereafter, the predicted results were compared with the experimental results to determine which of the two models give the most realistic results.

Furthermore, the influence of hydraulic performance on the separation efficiency of the bench scale IPS fed by a nozzle distributor is demonstrated in this study.

## 2. Material and method

Because of the inlet structure plays a very important role in determining the flow characteristics in the downstream particle separation zone (He et al., 2008), three inlet configurations were used to investigate the impact of feeding the IPS via a nozzle distributor on its hydraulic behaviour and separation efficiency. Sketches of the employed inlet structures are shown in Fig. 1.

The IPS was made of plexiglas of 15 mm in thickness with internal dimensions of (100 mm × 80 mm × 480 mm) and was placed on a ramp with angle of inclination 45° in all tests. Three polyvinylchloride plates 300 mm long and 5 mm thick were used in the IPS. The three plates could be fixed at any distance from the nozzle apex, and the spacing between the plates was 15 mm.

### 2.1. *Experimental set-up and procedures*

Two techniques were used to identify the hydraulic behaviour of the IPS. The first technique was measurement the velocity within every settler by using the colour velocity measurement (CVM) method (United States Department of the Interior Bureau of Reclamation, 1997). The second method was used to quantify the hydraulic behaviour of the IPS by using residence time distribution (RTD) experiment. Furthermore, to explore the impact of using distribution nozzle on the separation process, the removal of suspended solids (SS) efficiency for the IPS was determined.

A small slug of concentration dye solution (potassium permanganate) was injected impulsively into the IPS inlet, and a high resolution digital camera was used to provide the data for the calculation of mean velocity within every settler by computing the required mean time for the dye to travel a known length.

The RTD was measured by quickly injecting 3 mL of tracer (KCL, 3 g/l) into the IPS inlet and the tracer concentration at the outlet was measured with a conductivity probe every 5 s using a data acquisition system. The experimental procedures were repeated five times for each flow rate. The fitting of curve was then performed to minimize the deviation between the experimental data and the simulation data by using exponentially modified Gaussian peak function which has given us adjusted $R^2$ values between 0.94 and 0.97.

The separation efficiency was determined by specifying the concentration of SS in the samples which were collected from the inlet stream and outlet stream. The samples were filtered under pressure through a 0.45 μm pore size cellulose nitrate membrane using a compressed air filter model 16249 from Sartorius AG. This was followed by dry mass concentration analysis using a moisture analyser model MA45 also from Sartorius AG, Germany (Okoth et al., 2008).

To carry out these tests, an experimental set-up was constructed. A process flow diagram of the experimental set-up is shown in Fig. 2. It consists of a 35 L storage tank with an aerator mounted at the bottom denoted as A. This tank was filled with tap water in both velocity measurement and RTD experiments, while it was filled with suspension – including crushed walnut shell particles – in the separation efficiency test. The feeding of fluid was achieved by using a centrifugal pump denoted as B. The flow rates were regulated by using variable direct-current voltage power supply in a range of 0–24 V. There is a flow meter between the pump and the inlet, denoted as C. Both the conductivity meter and data acquisition system – denoted as D and E – were used only in the RTD test. To determine the separation efficiency, three sets of samples were collected from both the inlet stream (Section 1) and the outlet stream (Section 2).