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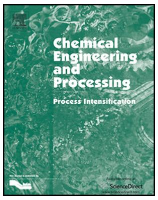

The theoretical densimetric Froude number values with favourable effect on the clarifier performance

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ABSTRACT

The performance of secondary clarifiers is strongly related to density effects in the sedimentation vessel. The upper level of the clarifier's chamber – once considered to be inactive at the sedimentation process – now appears to play an important role in solids removal. A fully developed three-layer flow phenomenon that develops in some cases is proved to promote settling. Therefore, investigation of flow patterns at different operative conditions was carried out. Experiments were conducted in a model of a circular, centre-feed settling tank with continuous operation. Ground hazelnut shells served as the settling matter; in one set of experiments only dye was used. All laboratory runs were filmed and analysed, qualitatively and quantitatively, by means of computer-aided visualisation. The results of the study showed that a determining factor of the conditions favourable for formation of a fully developed three-layer flow is the theoretical densimetric Froude number. If the hydraulic and solid loadings are soundly chosen in accordance with these findings, the clarifier performance can be evidently improved.

1. Introduction

1.1. Efficiency of settling tanks with continuous operation

Secondary settling tanks are an important element in the wastewater treatment process. The pollutant particles are removed from water by means of sedimentation. The main principle of sedimentation is conceptually simple: it allows the separation of the solid and liquid phases from the suspension that enters the sedimentation vessel, such as a settling tank. The incoming suspended solid particles settle down and form a sludge at the bottom of the sedimentation vessel. The remaining suspension (effluent) leaves the vessel and could be reintroduced if the operation of the sedimentation vessel is continuous. One of the important measures to determine the sedimentation vessel suitability is its sedimentation (separation) efficiency, which can be assessed through the amount of settled material or the quality of the effluent over a certain period of time. The sedimentation efficiency is influenced by several parameters of the suspension and the sedimentation vessel on both, the macro- and micro-scale.

The main characteristics of batch clarifiers operation had been investigated and mathematical models providing results with sufficient agreement to laboratory experiment had been developed [1,2]. However, flow dynamics in the settling tanks with continuous operation is much more complex, so a general parameter that would determine the efficiency of clarifier has not been established yet. Overdesign due to lack of knowledge of hydraulics in sedimentation tank is common and leads to unnecessary capital and operating expenditure [3].

1.2. Typical flow patterns

The density difference between the inflow and medium in the settling vessel has significant influence on the flow characteristics in the clarifier [4,5]. First attempts to postulate the effects of flow pattern in a sedimentation vessel resulted in an assertion that the gravity currents in a settling tank decrease the sedimentation efficiency [6,7] and are therefore unwanted. The following researches showed that this is not necessarily the case. Several laboratory experiments conducted on different types of clarifiers [8–10] had shown that the density effect stabilises the flow pattern and improves the efficiency of settling in the tank. The situation is contrary when the density difference derives from the influent being warmer than the tank content; due to the temperature disparity the clarifier exhibits a rising buoyant plume that changes the direction of the main circular current [11,12]. These short-circuiting currents keep the particles in suspension and lead to a higher effluent suspended solids concentration, thus, worse settling [13].

A pronounced gravity flow at the bottom and a reverse flow in the upper level is the standard pattern in a clarifier with continuous

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operation reported by several authors [8,14,15]. At the initial stage the flow pattern evolves in two main currents. At the bottom of the tank gravity current of fresh suspension is formed. It flows towards the outer wall where it turns upwards and splits in two directions. A part of the flow leaves the tank as the effluent; the other part flows towards the feedwell in the top layer of the sedimentation vessel.

In the first stage a two-layer flow pattern develops: the fresh suspension enters through the inlet orifice; the flow then turns downwards as a density waterfall along the feedwell baffle and divides at the bottom of the model settling tank [8]. A part of the flow turns back upwards and forms a vortex in a vertical plane of the inlet region. The other part of the suspension flow continues along the bottom into the inner chamber of the model tank. A strong density current forms along the bottom of the tank. The fresh suspension flow continues towards the outer wall of the settling tank, where it is directed upwards along the outer wall. A part of the fresh suspension flow runs directly out of the tank as the effluent, while the other part of the flow turns towards the inlet of the tank.

Results of several laboratory experiments indicate that the standard initial stage two-layer pattern in certain conditions changes and a three-layer flow pattern is formed that turned out to improve the clarifier's efficiency [8–10]. When equilibrium is reached, the main flow of suspension in the inner chamber, which flows upwards along the outer wall of the model, now turns towards the feedwell before even reaching the effluent weir. The short circuit effect is thus suppressed and the residence time of particles inside the inner chamber is prolonged [8]. Besides, in the upper level – a region of low concentration – a new current develops that now forms the effluent.

1.3. Densimetric Froude number

The relative importance of inertial and density gravity forces in a sedimentation vessel can be described in terms of the influence of momentum and buoyancy flux which is characterised by the densimetric Froude number Fr_d. If the mean flow velocity $\bar{v}$ at a selected cross-section is assumed to follow the continuity equation for non-compressible fluid:

$$\bar{v} = \frac{Q}{A} \tag{1}$$

where Q and A denote the flow rate and the selected cross-section area, respectively, the densimetric Froude number Fr_d can be formulated as:

$$Fr_d = \frac{\bar{v}}{\sqrt{\varepsilon \cdot g \cdot h}} \tag{2}$$

where g denotes gravitational acceleration and h is the height of the flow at the selected cross-section (at the inflow and in the middle cross-section, respectively). ε denotes relative density difference:

$$\varepsilon = \frac{\rho_i - \rho_{tank}}{\rho_{\text{tank}}} \tag{3}$$

where ρ_i and ρ_{tank} denote density of influent and density of the fluid inside the tank, respectively.

The relevance of the densimetric Froude number in assessments of flow features in a settling tank was taken in consideration by several researchers, whereby the selected cross-section was either at the inflow ($Fr_{d.0}$) and/or at the middle cross-section ($Fr_{d.m}$), respectively. Zhou et al. [16] investigated the effect of the inlet densimetric Froude number in secondary circular clarifiers by application of a verified numerical model; they found optimal operation when the value of $Fr_{d.0}$ was between 0.38 and 0.58. Van Marle and Kranenburg [10] carried out physical investigation on model settling tank with a constant densimetric Froude number value at the inlet ($Fr_{d.0} = 0.11$) to establish the influence of design modifications; a three-layer flow pattern was observed in all experimental cases. Ueberl [17] concluded that the length of a density current relative to the inlet height depends mainly of the densimetric inlet Froude number. Ueberl and Hager [18] carried out a research on a prototype rectangular settling tank. On the basis of their findings they recommended that the densimetric Froude number at the inlet ($Fr_{d.0}$) should be between 0.5 and 2 to generate a stable and nearly plane flow. Krebs et al. [9] investigated the correlation between the densimetric Froude number and the occurrence of a three-layer flow structure in a rectangular clarifier; different geometry and operation parameters (concentration and flow rate) were studied. They reported that for $Fr_{d.m} = 0.08$ partially and only for $Fr_{d.m} = 0.04$ fully developed three-layer flow was formed.

The (non)occurrence of beneficial three-layer flow pattern in the rectangular sedimentation vessel is proven to be related to the theoretical densimetric Froude number [9], however the threshold value for a circular clarifier has not been investigated yet. Circular tanks with denser influent are reported to be subject to shallower and higher velocity bottom density currents compared to rectangular tanks [19], so the characteristic range of Fr_d may not be the same. This paper presents a study of the relation between the three-layer flow pattern and the theoretical densimetric Froude number for a circular sedimentation tank with continuous operation. The flow pattern is to be identified (and classified) qualitatively and quantitatively.

2. Materials and methods

2.1. Physical model

A model settling tank was constructed in order to observe flow features and sedimentation efficiency in circular continuous settling tanks. The investigated prototype is an industrial settling tank that is used for water treatment by smaller industrial plants and is therefore small compared to the clarifiers that are being used in municipal water treatment plants. The model represented a radial section of the real circular settling tank in 1:1 scale, where axisymmetry around the vertical axis was assumed. The tank is made entirely of plexi-glass in order to facilitate visualisation of flow structures inside the tank. Such section enabled the clear observation of flow structures over the whole height of the vessel from the inlet part of the tank to its outlet orifice, which in the case of a whole circular tank would not be possible.

The bottom wall of the basin is inclined sloping upwardly towards the outer wall. The inner length of the model settling tank (L) is 890 mm, other important dimensions can be found in Fig. 1. Model settling tank was designed according to WEF recommendations [20]. The suspension enters the inner chamber of the tank through an orifice below the upper cover and leaves the tank at its outer edge (i.e. at the perimeter in the case of a circular tank). A baffle is placed just below the upper cover and close to the inlet orifice in order to prevent the fresh suspension to flow directly towards the effluent orifice. This baffle represents the outer edge of the feedwell on a circular settling tank. The height and position of the baffle was chosen according to relevant specifications and recommendations [20].

When representing a circular settling tank by a radial sector model certain deviations from the prototype cannot be avoided. While the peripheral outer wall adequately represents the cylindrical boundary of the sedimentation vessel, there are other two vertical outer walls which change the hydraulic conditions. Their position matches with the main vanes in the prototype; however the vanes do not extend throughout the entire length of the settling