NUMERICAL STUDY OF THE FLOW IN AIR FLOTATION SYRUP CLARIFIERS

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Abstract

Flotation clarification has been successfully introduced on an industrial scale in numerous liquid-solid separation processes, including the clarification of syrup in sugar factories, where reductions in colour, turbidity and suspended solids are achieved that are particularly beneficial in the direct production of white sugar. This paper presents results on the numerical simulation of the flow in syrup flotation clarifiers applying Computational Fluid Dynamics (CFD). Use is made of results from an experimental study of the hydrodynamic behaviour of the flocs. Based on the predicted flow field, the dynamic response of the clarifier has been simulated using the species model to obtain a ‘virtual’ residence time distribution, which is compared with results on tracer tests performed in a Tongaat-Hulett sugar mill. It is concluded that single-phase CFD solutions cannot describe correctly the flow in syrup clarifiers, where the buoyancy of the flocs appears to affect the flow field. The application of the Eulerian-Eulerian multiphase model has given better agreement with tracer results, and indicated possible flow patterns within syrup clarifiers. The numerical analyses suggested significant effects of the size of the flocs on the flow, the positioning of the outlets and the existence of stagnant zones. The introduction of inclined channels, or ‘lamellas’, within the flotation area to optimise the flow patterns is discussed, concluding that they are effective in preventing recirculation and turbulence, and could help to increase the throughput of syrup clarifiers substantially.

Keywords: clarification, flotation, syrup, CFD, separation, DAF, factory process

Introduction

Separation by flotation is achieved by generating fine air bubbles and creating appropriate conditions for attachment to the materials to be removed. As a result, agglomerated particles or ‘flocs’ are formed, which have a lower density than the surrounding liquid due to the air content. This results in buoyancy forces that cause the flocs to rise to the free surface, where a scum layer is formed that can be easily removed. Dissolved air flotation (DAF) has been used for years as a separation technique in the treatment of drinking and waste water, for mineral processing, in the oil industry, and in paper mills, where solids, fibres, ions and macromolecules are removed; it can also help in reducing the biological and chemical oxygen demands. In the case of the sugarcane industry, flotation has found application in the treatment of refinery liquors, syrup, filtrate and waste waters.

Syrup clarification by flotation improves the quality and viscosity downstream, improving boiling operations and sugar quality (Rein *et al*, 1987). Trott (1988) described this process, including the following stages: heating, phosphatation, aeration, flocculation and flotation. Rein *et al.* (1987) presented a method for reproducing the process in a simplified laboratory test, and reported on the effect of various factors. They concluded that the removal of turbidity is dependent on temperature up to ~85ºC and further increases give no improvement. Similarly, it was observed that the addition of phosphate and lime could be eliminated, and other variables such as brix, pH and viscosity do not have a significant effect on the separation efficiency. Smith *et al.* (2000) recommended a subsequent cooling of the syrup to avoid sugar losses and colour formation. Steindl and Doherty (2005) indicated that flotation can replace sulphitation for syrup treatment, being an alternative for enhancing the colour of 'blanco directo' sugar without increasing the residual sulphur dioxide content. Table 1 summarises data that have been presented on the removal of impurities in syrup flotation clarifiers.

Table 1. Removal of impurities in syrup flotation clarifiers.

Source	Turbidity	Colour	Ash
Rein *et al.* (1987)	80-95%	15%	–
Trott (1988)	80%	up to 10%	up to 10%
Chen and Chou (1993) Taiwan	68-89%	18%	–
Smith *et al.* (2000) Flotation	77%	7%	–
Sulflotation	77%	15%	–
Steindl & Doherty (2005) Final - 4th effect	86%	–	–
Intermediate - 3rd effect	54%	–	–
Factory 1	92%	10%	3.6%
Factory 2	90%	No change	10.6%

Different alternatives are available for the generation of the bubbles and, in sugar mills, DAF is normally used, involving injection of air at the suction of a centrifugal pump or stirrer or through fine spargers. An anionic flocculant is then added to promote the formation of the flocs and to attach the air bubbles. The optimum flocculation parameters vary according to particular conditions, and can be determined from small-scale tests.

Results of a study of settling clarifiers have indicated that numerical computational fluid dynamics (CFD) solutions that match reasonably well with velocity measurements can be obtained considering only liquid flow with single-phase models (Szalai *et al.* 1994) that can be easily solved after simplification of the geometry and boundary conditions. On the other hand, experimental results obtained for flotation clarifiers have illustrated changes in the flow field as air is injected; evidence of a phase interaction that affects the flow field (Lundh *et al.* 2001). This could be a consequence of the density differences, and as a result the accurate solution of this flow requires a multiphase model. This results in a more complex situation, where the agreement between computations and measurements has been reported to be difficult (Ta *et al.* 2001). For sugar applications, Peacock *et al.* (2000) and Steindl (2001) presented numerical predictions of the flow in the Rapidorr 444 and SRI juice settling clarifiers, respectively. No experimental or numerical results have been reported for flotation syrup clarifiers. This paper presents results obtained in a numerical analysis of the flow in a full-scale syrup clarifier, which are validated by comparison with residence time distribution curves determined from tracer tests. Simulations are performed to identify probable flow patterns and explore the effects of potential changes in the design to improve the hydrodynamic characteristics within the flotation region.

Materials and Methods

A syrup clarifier that operated in the Tongaat-Hulett Empangeni sugar mill was chosen as the study case, where geometry and residence time distribution were presented by Rein *et al.*

(1987). Figure 1 illustrates the geometry of the clarifier and the grid generated for the numerical solution of the flow using CFD.

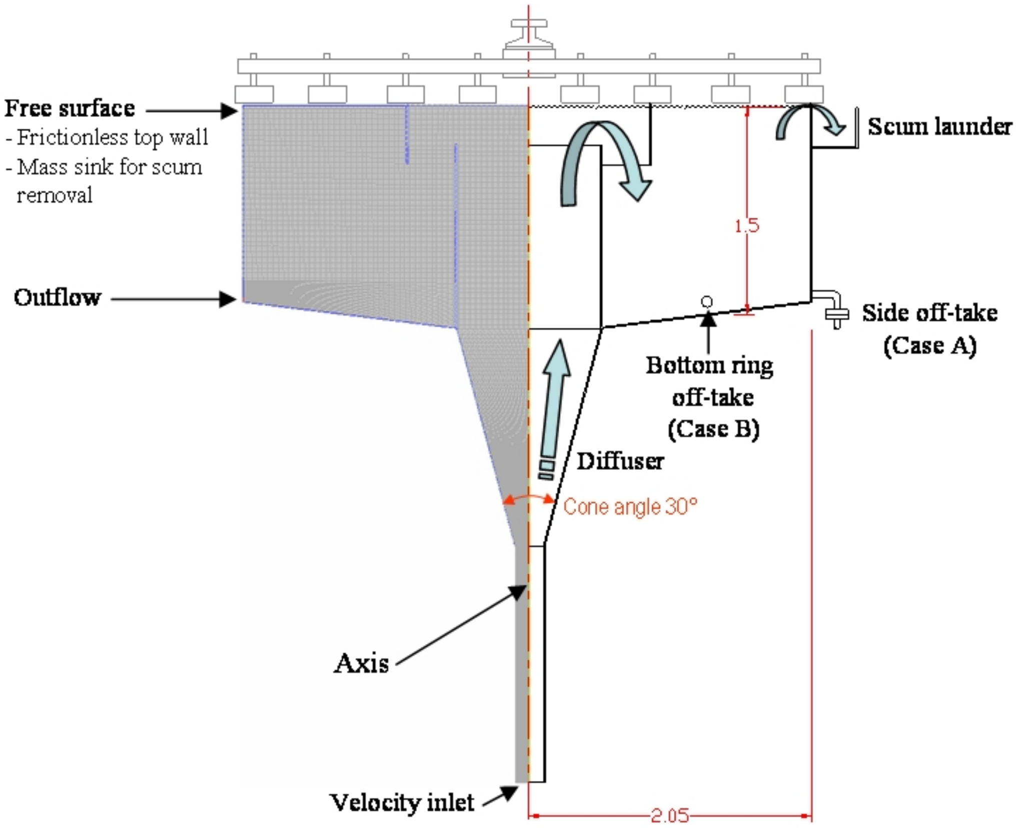


Figure 1. Schematic representing (a-right side) the cross-section of the air flotation syrup clarifier studied, and (b-left side) the mesh used for computational fluid dynamics (CFD) analysis [2D, 50762 nodes].

For the simulations, the commercial CFD code FLUENT was used to perform single-phase and multiphase analyses. As shown in Figure 1, the geometry of the clarifier was simplified to obtain an axisymmetric case that conveniently reduces the problem to a 2-D domain, lowering the computational work required. The k-ε turbulence model is applied, and a steady state situation is assumed. The liquid and scum phases enter into the computational domain through a velocity inlet boundary condition located at the bottom, representing the pipe line feeding the diffuser. The free surface is represented using a frictionless wall at the top boundary, removing the secondary phase with a mass source, while the liquid exits through outflow boundary conditions located at the side or the bottom of the flotation cell, defining two different cases A and B correspondingly. Considering the apparent quiescence of the scum layer, the agitation produced by the slow moving scraper is neglected. The flow is assumed isothermal (~85°C), and therefore it is not necessary to solve the energy equation.

No previous studies on the flow in flotation syrup clarifiers have been reported, and the only dependable information related to the flow that is available is residence time distribution (RTD) curves. For the particular study case, Rein *et al*. (1987) presented results obtained with tests using lithium chloride as a tracer. In this work the RTD curves are computed using the species model, without reactions, simulating the test by injecting a tracer pulse at the inlet and monitoring the content of the tracer at the outflow, where the syrup leaves the computational domain. An ideal pulse is assumed, with negligible mass diffusion and the tracer exhibiting the same properties as the liquid phase.

The flow within the syrup clarifier is initially solved using a single-phase model (only syrup), giving a frame for comparison with multiphase analysis on the effect of the secondary phase (scum) in the flow field. For the multiphase analysis the Eulerian-Eulerian model is chosen, assuming that the flocs behave as solid particles, and applying the Schiller and Naumann drag coefficient correlation to model the inter-phase momentum interaction.

Lab-scale clarification tests were performed following the technique described by Rein *et al.* (1987), but oriented to determine the quantity of scum produced and its density, information that is required for setting the CFD multiphase simulations. The flotation tests were performed in a Pyrex container, and a high-speed camera was used to record the rising of the scum, giving information on the characteristics of the float and its rise velocity.

Results and Discussion

Lab-scale syrup clarification

In the laboratory syrup flotation tests, a turbidity removal of 75% was achieved using an anionic flocculant (20 mg PCS 3020/kg DS). It was observed that at the end the scum occupied ~14% of the total volume, and represented ~5% of the total mass. The density of the scum produced was determined to be around 450-500 kg/m^3.

The analysis of the images recorded during the tests showed a chaotic process at the beginning, with the scum rising more as a disordered ‘froth’ than distinguishable flocs. Initially the froth velocity is relatively high and back-flow is generated near the walls, suggesting strong interaction between the phases and buoyancy effects, which could be significant in the flow in full-scale clarifiers. As the process continued, a compaction mechanism was observed near the free surface, where the scum accumulates progressively as the rising velocity of the flocs reduces. Due to the disordered character of the flotation, it is difficult to determine the velocity accurately from analysis of the images, but it can be said that the scum-syrup interphase decelerates progressively from 0.6 mm/s to zero, while flocs below this interphase rise faster, showing an increase in the momentum interaction with concentration. Floc velocities between 0.3-4.7 mm/s (1.4 mm/s on average) were recorded, corresponding to particles with size 79-342 µm (183 µm on average). Without floc formation the air bubbles rise between 0.2-0.8 mm/s, suggesting sizes between 55-109 µm.

The quantity of scum obtained during the lab-scale tests was significantly higher than the 5% by volume reported by Rein *et al.* (1987). It is considered here that, on a lab-scale, the probability of bubbles escaping is lower than in a full-scale clarifier, and consequently the amount of scum would be higher. Rein *et al.* (1987) suggested that only 40% of the injected air was dispersed in the liquid, while a significant part was released in a separation tank before the clarifier.

Simulation of the flow in the Empangeni syrup clarifier applying CFD

The conditions considered for the numerical simulation of the flow in the Empangeni syrup clarifier are based on the throughput and operational variables of the clarifier in 1982, assuming the properties of the scum determined in the lab-scale tests. Table 2 summarises the main parameters considered in the analysis of the flow and the residence time distribution.

Table 2. Parameters used in the numerical analysis of the flow in the Empangeni clarifier.

Syrup	Flow (t/h)	59.7
	Density (kg/m^3)	1270
	Viscosity (Pa.s)	0.01
Scum/flocs	Density (kg/m^3)	500
	Volumetric fraction	5%
Tracer	Mass (kg)	0.875

Single-phase flow predictions

Figure 2 presents the streamlines and RTD predicted for the two cases with single-phase simulations. This indicates that within the flotation cell a main liquid stream flows, attached to the internal and bottom walls, travelling almost straight from the central-feed to the offtakes, while a large vortex is developed in the rest of the domain. For this single-phase situation it appears that the liquid initially flows in the same feeding direction, downwards, as the axial momentum has to be conserved, and then is deflected by the bottom wall in the radial direction. A large portion of the flotation cell would be under-utilised according to these results.

A flow separation is predicted in the inlet diffuser, which is a consequence of the large expansion and angle of the cone (30º, see Figure 1). Angles around 6-7º are used in diffusers to prevent separation and minimize frictional losses. This problem will not be discussed here in detail, but it is considered that small geometry changes or adding deflectors could easily prevent this separation occurring.

As quantifiable parameters for the analysis of the RTD curves, the short-circuit time (t_{SC}) and peak time (t_{PK}) are evaluated, which correspond to the periods elapsed between the injection of the tracer in the clarifier and its first appearance and maximum concentration in the outflow, respectively. It is assumed here that the short-circuit time corresponds to the instant when the tracer concentration reaches the order of parts per million (ppm).

The 'virtual' RTD curves predicted with single-phase simulations exhibited peak times significantly lower than those measured and higher peak concentrations (C_{PK}), as can be observed in Figure 2. The low residence time predicted is a consequence of the computed flow field, where most of the syrup flows through a relatively small portion of the volume. The RTD curve predicted for the bottom offtake is narrower than for the side offtake, displaying a lower peak time (5.6 vs 7.6 min) and higher peak concentration (187 vs 150 ppm). This result appears reasonable, since the bottom outlet is located closer to the central feed, and the liquid travels a shorter distance. However, from a qualitative point of view this is opposite to the tracer test results, which showed a larger peak time after the offtake was changed from the side to the bottom.

In reality, the tracer was added in an air-release tank ahead of the clarifier, and the pulse is obviously non-ideal, so differences between the predicted and measured tracer tests are expected. However, the agreement between the RTD predicted and measured is poor from both qualitative and quantitative points of view, suggesting that the single-phase model is inappropriate for the study of the flow in syrup flotation clarifiers.

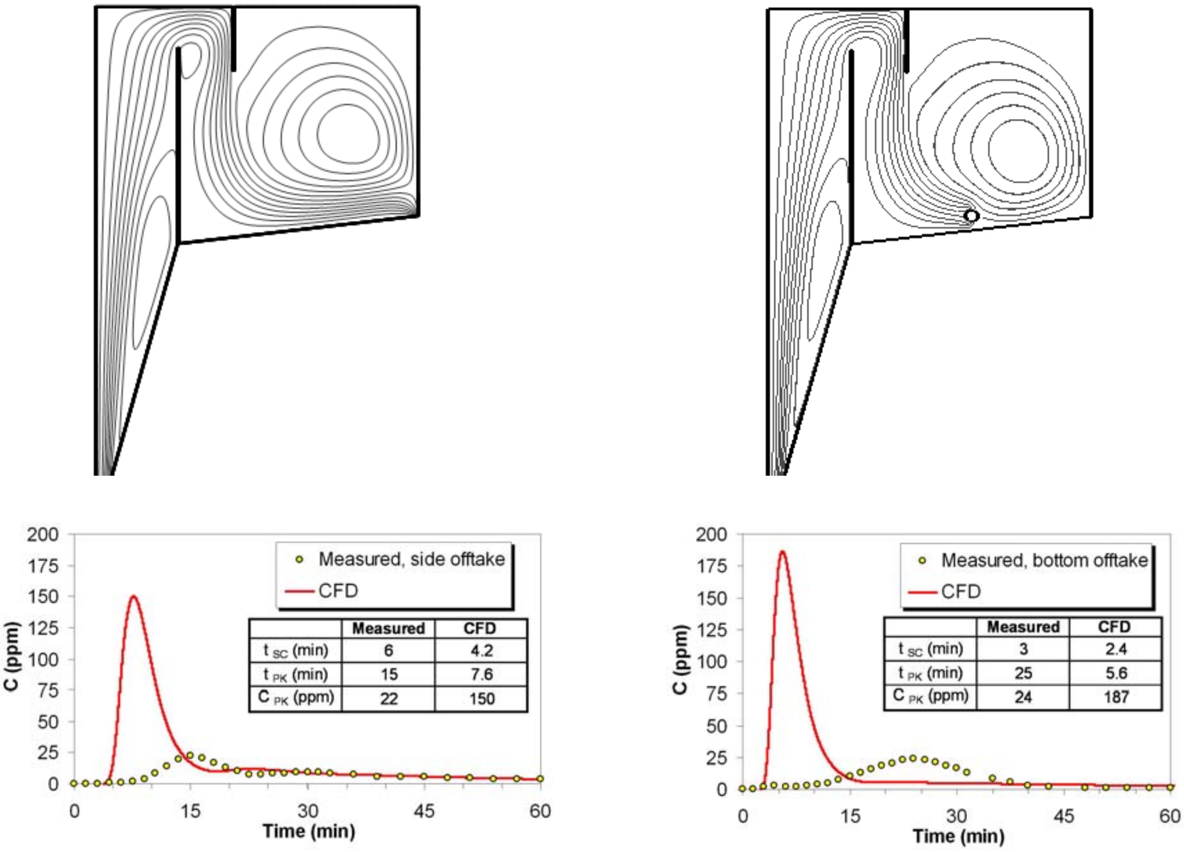


Figure 2. Streamlines and RTD predicted with single-phase models for (a-left) side offtake and (b-right) bottom offtake cases, and tracer test results (Rein *et al.* 1987).

Two-phase flow predictions

Making use of the lab-scale flotation results and assuming ideal spherical flocs with a density of 500 kg/m^3, it was estimated that their size could be around 150-220 µm. A range of floc sizes between 100-300 µm was evaluated in the multiphase simulations, showing substantial changes in the flow field. Figure 3 presents the predicted syrup and scum streamlines for the side-offtake case, assuming three different floc sizes. In general, it was observed that flocs smaller than 170 µm tend to follow the liquid phase and, as a consequence, a significant part does not separate. On the other hand, flocs larger than 250 µm rise quickly after entering the flotation cell and reach the scum layer close to the inner diameter.

It can be observed in Figure 3 that the multiphase flow prediction tends to approximate the single-phase solution as the size of the flocs is reduced. This behaviour indicates that the buoyancy effects increase with the size of the flocs, and points to the existence of an optimum floc size for the process.

Of particular importance is the finding that small flocs will be entrained with the underflow. It is important therefore from an operational point of view that the pre-treatment of the syrup leads to a large well-formed floc.

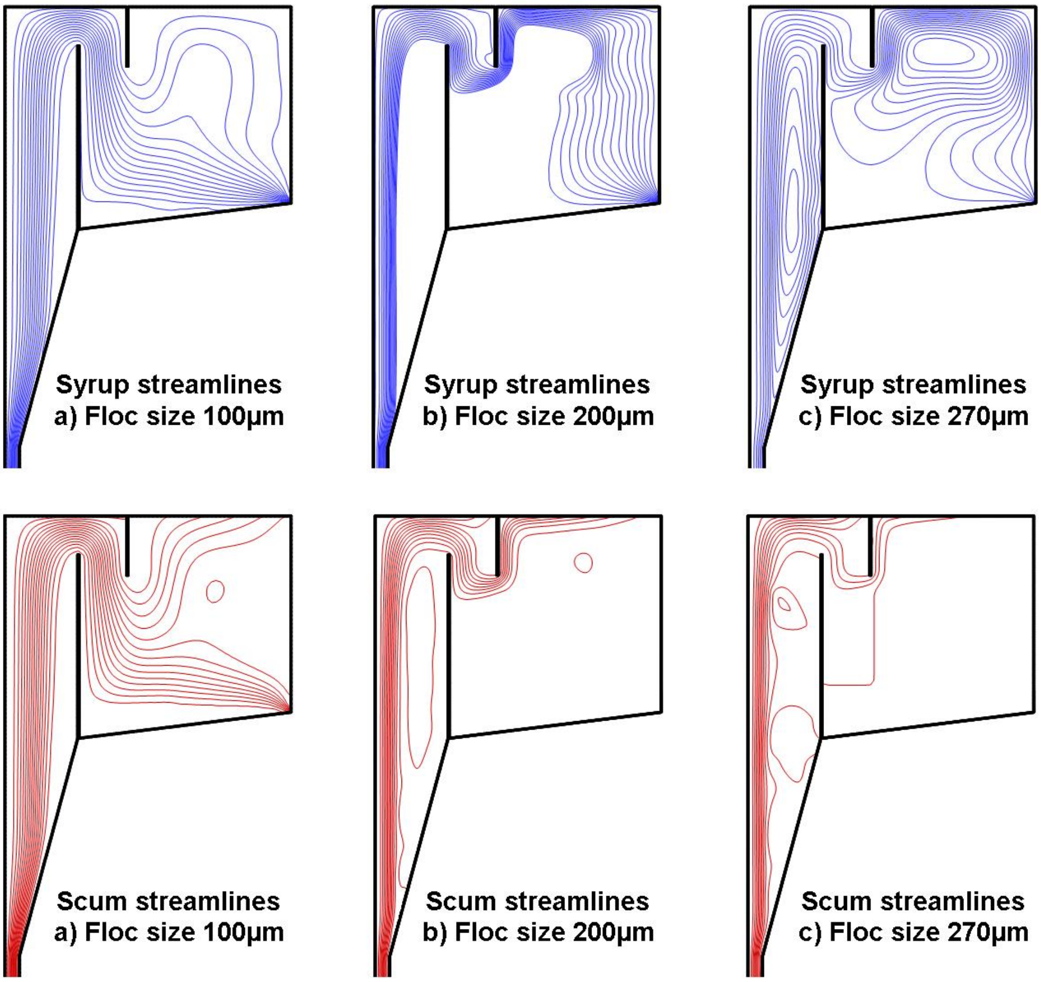
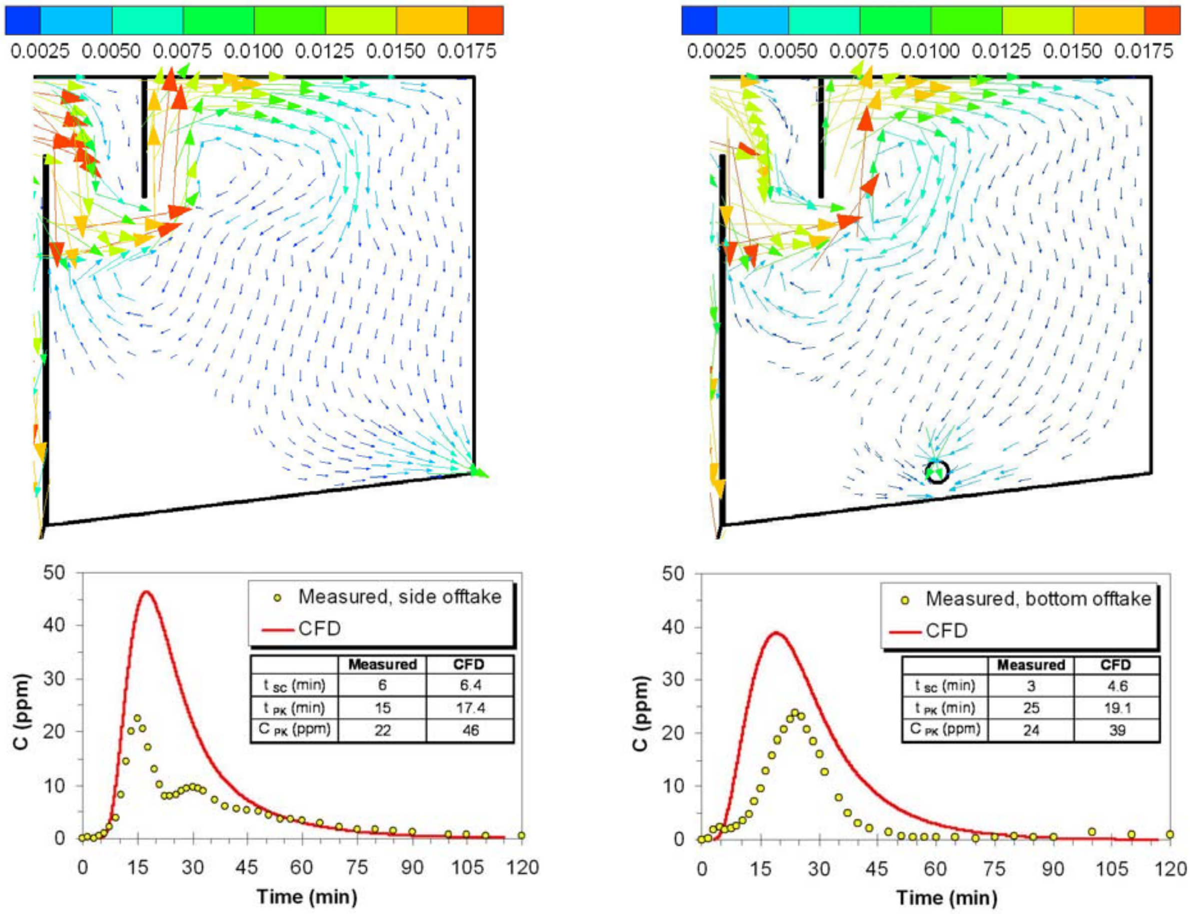


Figure 3. Liquid and floc streamlines predicted for the syrup clarifier with the multiphase model, considering three different floc sizes: 100 (a-left), 200 (b-middle) and 270 µm (c-right).

Effect of the offtake position

Considering the results discussed above, a floc size of 200 µm was chosen as representative. However, in reality a distribution of size exists and affects somehow the flow field, but at this stage is not possible to represent this effect in detail. Figure 4 presents the liquid velocity vectors and RTD predicted with the multiphase model for the two situations considered, discharging the syrup at the side and the bottom of the clarifier. They indicate that in both cases the syrup initially rises towards the free surface, as a consequence of the buoyancy forces associated with the floc, and then after the flocs separate, the liquid flows downwards to the offtakes. A relatively small vortex is generated towards the inner diameter of the flotation cell between the rising stream of syrup + scum and the descending floc-free syrup.

A slow-moving recirculation zone is predicted at the bottom of the clarifier (velocity <1 mm/s), which is slightly larger for the side-offtake case, and would help to explain the shorter residence time measured and predicted for this case. The predicted RTD curves show reasonable agreement with the measurements reported by Rein *et al*. (1987) with respect to the short-circuit and peak times, and qualitative similarity indicating a narrower curve for the side-offtake case or higher residence time for the bottom ring offtake. The flow field described is probably the only rational explanation for having longer residence times with the bottom ring, which otherwise would be shorter due to the proximity of the offtake to the feed channel.



	Measured	CFD
t_{SC} (min)	6	6.4
t_{PK} (min)	15	17.4
C_{PK} (ppm)	22	46

	Measured	CFD
t_{SC} (min)	3	4.6
t_{PK} (min)	25	19.1
C_{PK} (ppm)	24	39

Figure 4. Liquid velocity vectors [m/s] and RTD predicted with the Eulerian-Eulerian model when the liquid is removed through (a-left) the side and (b-right) the bottom of the clarifier. Velocity vectors below 1 mm/s are not displayed.

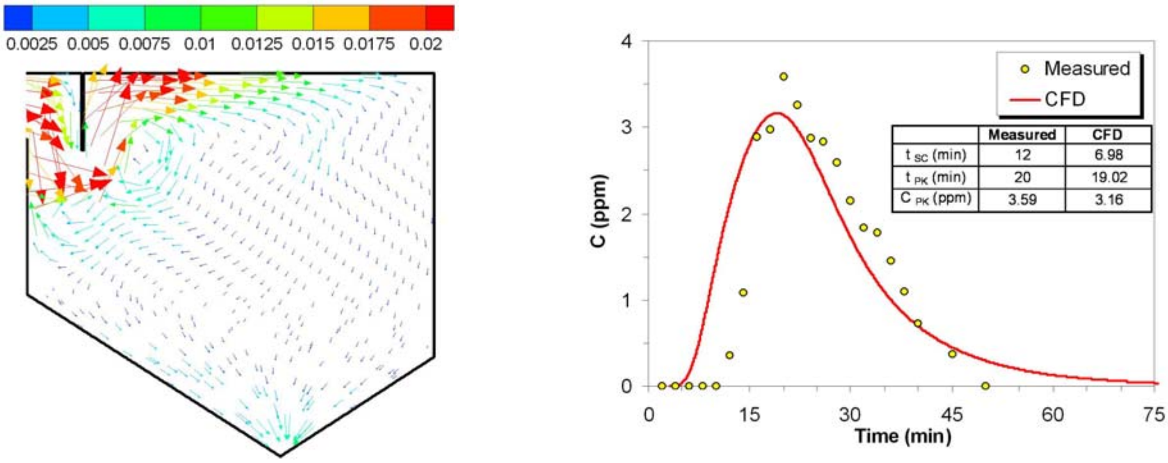
The concentration peaks predicted are higher than the values reported by Rein *et al*. (1987), but closer to the expected lithium concentration (44 ppm). This phenomenon could be associated with problems in the analytical methods for lithium in sugar streams reported by Barker (2004), who discussed the low recovery of lithium chloride from tracer tests in syrup clarifiers.

Unfortunately the similarity found between the simulated and measured RTD curves does not guarantee that the flow prediction is accurate, since this response is not unique and the same curve can represent diverse flow and mixing conditions. Nonetheless, the comparison has been useful in establishing that the single-phase solution is inappropriate for the analysis of syrup flotation clarifiers, and indicates that the multiphase solution obtained might be correct.

Potential ways of increasing the efficiency of syrup clarifiers

From the previous analysis, the following conclusions can be drawn on the hydrodynamics of the syrup clarifier studied:

- The velocity of the syrup feeding in the downward direction is the same as that experienced in sedimentation clarifiers, where the particles reach and separate at the bottom. In water flotation clarifiers the feed is often upward, and the simulations indicate that this could be the situation in the clarifier studied. The feeding arrangement could potentially be improved by a well-distributed low-momentum stream entering into the flotation cell in a radial direction at low velocity.
- The flow simulations indicate that the bottom ring off-take is better, agreeing with the tracer tests results reported by Rein *et al*. (1987). Studies on separation by flotation have shown that the removal of the clarified liquid is a key factor, and new designs incorporate high-resistance multiple distributed outlets, such as perforated lateral pipes, sand filters, and perforated plenum floors, which help to achieve a more uniform liquid down-flow and prevent the development of recirculating currents (Schofield 2001). The use of multiple openings or several perforated rings at the bottom of syrup clarifiers to remove the liquid might contribute to reducing recirculation in the flotation zone.
- The stagnant regions predicted in the bottom corners of the Empangeni syrup clarifier can be eliminated by improving the geometry of the flotation cell. Figure 5 presents numerical results for a more recent design installed in the Triangle sugar mill, where inclined walls are used at the bottom, forming a W-shape, which seems to prevent stagnation without any negative impact. The syrup offtake is located in this case at the bottom lowest point. The flow simulation indicates no large low-velocity regions and has shown reasonable agreement with tracer test results.



	Measured	CFD
t_{SC} (min)	12	6.98
t_{PK} (min)	20	19.02
C_{PK} (ppm)	3.59	3.16

Figure 5. Liquid velocity vectors [m/s] and residence time distribution predicted with the multiphase model for the Triangle syrup clarifier and measured by tracer test (vectors below 1 mm/s not displayed).

Use of lamellas

A breakthrough in flotation water treatment was the introduction of lamellas, which prevent vortices and reduce the Reynolds number, and consequently the turbulence, leading to a more efficient separation and higher capacity. The parameter typically used to describe the performance of clarifiers is the surface load rate, which relates the volumetric flow to the total plan flotation area, giving an average superficial vertical velocity. The surface load rates found in water settling clarifiers (1-2 m/h) are significantly lower than in flotation clarifiers (3-13 m/h), reflecting the benefit of a larger density difference between flocs and liquid, but flotation units provided with lamella plates can achieve even higher load rates (30-40 m/h). The Empangeni syrup clarifier exhibited a surface load rate around 3.8 m/h, within the low range found in water treatment for corresponding conventional flotation clarifiers.

Numerical simulation of the flow in a hypothetical syrup clarifier provided with lamellas has been performed following the same approach applied for the Empangeni case, and assuming the same flow parameters. The primary design has been defined based on the following considerations:

- *Surface-load rate:* It is assumed that a surface load of 20 m/h can be achieved, increasing this parameter by a factor of five.
- *Rectangular cell:* A rectangular geometry is considered to facilitate the array of the lamellas, although they have been introduced in circular tanks as well. The control of the hydraulics is simpler in rectangular tanks, and they are frequently used in flotation clarifiers.
- *Lamella length* (L): Assumed L = 1.22 m (48 in), a popular dimension in the market.
- *Lamella inclination (θ):* The inclination of the lamellas has a strong effect on the separation efficiency, and normally they are set around $\theta = 45\text{-}60°$ with respect to the horizontal. Hedberg *et al*. (1998) determined experimentally that low angles favour the separation, but below $\theta = 40°$ the bubbles tend to rise slowly under the plates. Considering the higher viscosity of syrup (than water), a conservative $\theta = 60°$ was selected for this analysis, although experimental information would be fundamental in determining the optimum inclination.
- *Horizontal distance between lamellas* (S): Considering experimental data presented by Hedberg *et al*. (1998), a separation of S = 50.8 mm was selected. A smaller gap would theoretically increase the capacity, but the separation of the smallest flocs could be affected.
- *Liquid distribution:* It is assumed that the liquid phase distributes evenly between the lamella channels. Distributed orifices at the bottom have been used to generate a small head loss to give an even distribution of the liquid through the lamellas.
- *Residence time:* The total volume of the projected clarifier is 5.54 m^3, and the ideal mean residence time for the 60 t/h flow of syrup would be $\tau = 7$ min. These values are significantly lower than in the Empangeni clarifier (19.9 m^3, $\tau = 25$ min).

Figure 6 presents the liquid flow streamlines and contours of scum concentration predicted for the syrup clarifier orienting the lamellas with and against the stream direction (but $\theta = 60°$ in each case). The results indicate two flow separations in the inlet diffuser, while the patterns above the lamellas show a relatively smooth flow, free of vortices. Although most of the separation seems to occur above the channels, it could be said that the lamellas are the factor guaranteeing complete separation, as the flocs cannot follow the liquid flowing downward within the channels. No plate orientation effects are evident, but it is considered here that orienting the lamellas against (b-right) might be better, avoiding potential flow separation at the top of the channels and/or re-entrapment of flocs into the same channel.

The responses of the clarifier to higher load rates have been evaluated numerically. These show an increase in the penetration of the scum into the lamella channels as the flow rate increases, which will lead to a reduction in separation efficiency. Figure 7 presents predictions for the processing of 100%, 200% and 300% of the nominal syrup flow rate (60 t/h), illustrating how the flocs occupy progressively a larger part of the channels as the syrup flow increases (0.11%, 0.85% and 1.64% by volume respectively). While processing 200% (40 m/h) appears feasible, the 300% case is considered here to be unacceptable, which in fact corresponds to a surface load (60 m/h), well above the limits achieved in water DAF units (30-40 m/h).

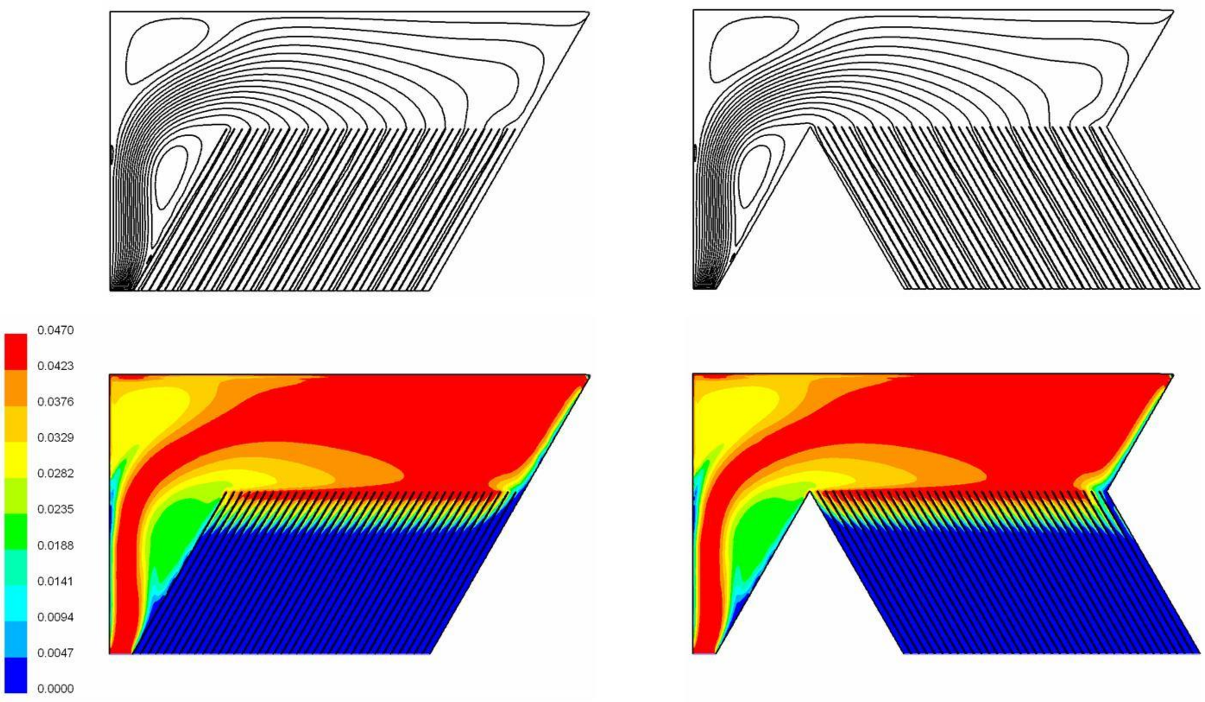


Figure 6. Syrup streamlines and contours of scum volume concentration predicted for a lamella syrup clarifier orienting the plates (a-left) with and (b-right) against the flow stream.

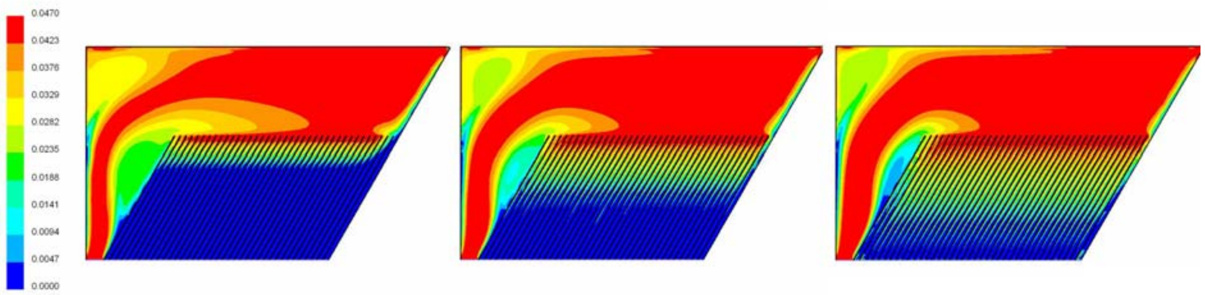


Figure 7. Contours of scum volume concentration predicted numerically for the lamella syrup clarifier processing (a-left) 60 t/h, (b-middle) 120 t/h, and (c-right) 180 t/h of syrup.

From experimental work, Hedberg *et al.* (1998) concluded that lamellas produce favourable hydraulic conditions that permit the small bubbles to reach the upper plates, where they can aggregate and rise, permitting dramatic increases in the capacity of DAF units. The mechanism described can be visualised in these numerical predictions, observing that the scum volumetric fraction is higher under the plates (Figure 6) and that a greater penetration into the channels is seen as flow rate is increased, increasing the distance required for the flocs to reach the upper lamella surface (Figure 7). Figure 8 presents the trajectories that flocs released from the top of a lamella channel would follow, illustrating a rapid rise of large particles (500-1000 µm) and a relatively rapid displacement to the upper plate of a medium size particle (200 µm), while small flocs (100 µm) would travel further down the lamellas before reaching the upper plate.

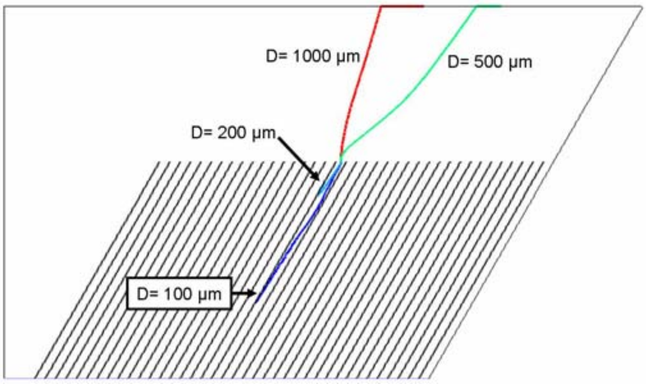


Figure 8. Traces predicted for particles (flocs) of different sizes.

The numerical results have illustrated the physical mechanism associated with the use of lamellas for flotation clarification, showing a combination of buoyancy and low velocity near the plate surfaces which allows the separation and rise of small flocs. This technology could help to improve significantly the capacity and efficiency of syrup clarifiers with uncomplicated and inexpensive changes in the design.

Conclusions

The flow in a syrup flotation clarifier has been studied numerically, illustrating important buoyancy effects and the necessity to perform multiphase calculations. The residence time distribution has been predicted using the species model, obtaining results that show reasonable agreement with tracer test measurements, although further experimental work would be useful for validation of the flow predictions. The floc size has a dramatic effect on the flow field and the separation efficiency in flotation clarifiers, and lab-scale tests have indicated lower rising velocity as the floc concentration is higher, evidence of an increase in the momentum interaction. The floc size is shown to be important in minimising entrainment out of the clarifier with the clarified syrup stream.

Alternatives for improving the hydraulic characteristics of syrup clarifiers have been illustrated. In particular, the application of lamellas in syrup flotation clarifiers is shown to improve substantially the capacity and separation efficiency.

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