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CFD ANALYSIS OF SHORT RETENTION TIME CLARIFIER

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ABSTRACT

Clarifiers are used in the sugar industry to remove particles from the raw cane juice that has been squeezed from the sugar cane. A clarifier works on the principle of slowing the liquid flows to allow the solid phase to settle out under gravity. Flocculants are added to the feed stream to assist the settling process. The clear cane juice leaves from the top of the vessel and the mud particles are removed from the mud thickener at bottom. This paper reports on Computational Fluid Dynamic (CFD) analysis of Short Retention Time (SRT) clarifier having peripheral feed entry and concentric take off. SRT clarifier is continuous type with a juice retention time of around 20 to 30 min compared to 2 to 3 hrs in conventional multiple tray type clarifiers. CFD analysis of the clarifier involves the two phase modeling of clear cane juice as a liquid and mud particles as a solid. CFD model solves mass, momentum, energy, kinetic energy and phasic equations for the given flow field variables. CFD tool ANSYSY FLUENT is used to assist in understanding the fluid flow profiles within the clarifier and to assess the impact of design variations on the fluid flows and mud separation. 2D axisymmetric model of SRT clarifier was built and physical boundary conditions are applied. Internal flow field in the settling zone of the clarifier was studied for varying inlet feed velocities. The results of the CFD model are discussed. Turbidity of clear cane juice from new SRT clarifier is measured at the factory.

NOMENCLATURE

α_q	Volume fraction of phase *q*
ε	Turbulent energy dissipation rate
ρ_q	Density of phase *q*
$\overline{\overline{\tau}}_q$	Stress-strain tensor of phase *q*
$\vec{F}_q$	External body force
$\vec{F}_{lift,q}$	Lift force
$\vec{F}_{vm,q}$	Virtual mass force of phase *q*
$\vec{g}$	Gravitational acceleration
k	Turbulent kinetic energy
$\dot{m}_{pq}$	Mass transfer from the p^{th} to q^{th} phase
$\dot{m}_{qp}$	Mass transfer from the q^{th} to p^{th} phase
p	Pressure
$\vec{R}_{pq}$	Interaction force between p^{th} and q^{th} phases
S_q	Mass source term
t	Time
$\vec{v}_{pq}$	Interphase velocity between p^{th} and q^{th} phases
$\vec{v}_{qp}$	Interphase velocity between q^{th} and p^{th} phases
$\vec{v}_q$	Velocity of phase *q*
V_q	Volume of phase *q*

INTRODUCTION

The Short Retention Time (SRT) clarifier incorporating latest concept of peripheral feed and centrally take off launder is designed to handle cane juice for raw sugar or white sugar manufacture. The main advantages of the SRT clarifier are:

- Reduced retention time.
- High capacity per unit settling area

Conventional clarifiers of multitray design generally require 2 to 3 hrs for the mud particles to settle effectively under gravity by sedimentation. Conventional clarifiers have lower volumetric flow rate per hour compared to SRT clarifier.

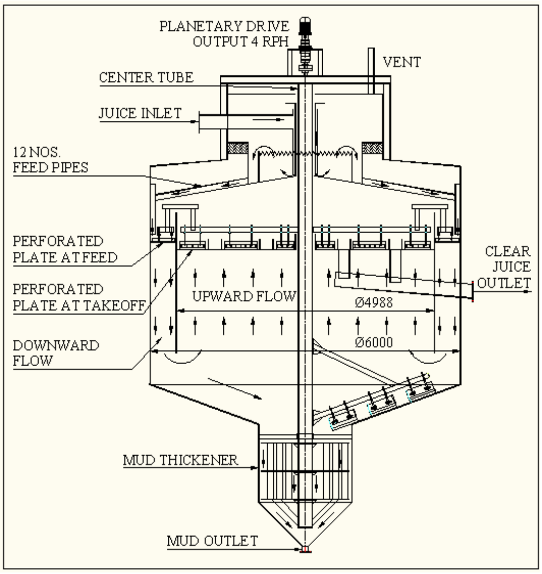


Figure 1: 2D diagram of SRT Clarifier.

The SRT clarifier consists of main cylindrical shell, top and bottom cone, juice feed launder, clear juice take off launders, mud thickener, and slow moving stirrer as shown in Figure 1. The main shell is fabricated from carbon steel plates. The bottom cone is design with adequate slope for assisting the transport of mud solids towards the mud thickening section in the base of the clarifier. The central rotating pipe shaft is driven by the motor fitted on the gear box which gives rotation to the central shaft of 4 rpm. The drive assembly is mounted on a carbon steel fabricated bridge. Scraper arms are fitted on the central rotating shaft by arm holder with four branch connections. Trailing type scrapers are hinged to scraper arms to remove the mud particles settle on bottom cone.

Cane juice is flashed to remove entrained air before it enters the clarifier feed inlet. Flocculent is mixed with cane juice to build up dense and heavier flocs for enhancing mud settling properties. The feed juice is directed to the feed launder which uniformly feeds the cane juice peripherally through branched juice distribution pipes. These pipes are designed to achieve uniform distribution to the peripherally located feed well. The cane juice then flows down the feed well as shown in Figure 1 before entering into the settling zone where clear juice rises up and mud solid particles settle to the bottom of the clarifier. Clear juice is removed by concentric outlet launders. Perforated plates are provided at the top of peripheral feedwell for uniform cane juice distribution and also near the top of the clarifier at the clear juice take off zone for removing juice flow evenly from across the whole clarifier surface.

The flow pattern inside the SRT clarifier is not visible. Vortex formation and reverse flows can disturb the settling zone of the clarifier and affect the clarity of cane juice giving adverse effect on capacity throughput.

The objectives of the research were,

- Study of the flow pattern within the clarifier
- Optimization of flow rates
- Improvement in the clear cane juice quality

CFD MODEL DESCRIPTION

Multiphase model of the clarifier was formulated and solved using commercial software ANSYS FLUENT 12.0. CFD analysis of the clarifier involves two phase modeling of clear cane juice as liquid and mud particles as solids. A steady state Eulerian-Eulerian 2 phase model is used with standard *k-ε* turbulence model.

The volume fraction of each phase in Eulerian multiphase flow is calculated by phasic equation (1).

$$V_q = \int_V \alpha_q dV \quad (1)$$

Where $\sum_{q=1}^{n} \alpha_q = 1$

Conservation Equations

Conservation of mass and momentum equations (2) and (3) are solved for each phase individually

$$\frac{\partial}{\partial t}\left(\alpha_q \rho_q\right) + \nabla \cdot \left(\alpha_q \rho_q \vec{v}_q\right) = \sum_{p=1}^{n}\left(\dot{m}_{pq} - \dot{m}_{qp}\right) + S_q \quad (2)$$

$$\frac{\partial}{\partial t}\left(\alpha_q \rho_q \vec{v}_q\right) + \nabla \cdot \left(\alpha_q \rho_q \vec{v}_q \vec{v}_q\right) = -\alpha_q \nabla p + \nabla . \bar{\bar{\tau}}_q + \alpha_q \rho_q \vec{g} + \sum_{p=1}^{n}\left(\vec{R}_{pq} + \dot{m}_{pq}\vec{v}_{pq} - \dot{m}_{qp}\vec{v}_{qp}\right) + \left(\vec{F}_q + \vec{F}_{lift,q} + \vec{F}_{vm,q}\right) \quad (3)$$

ANSYS FLUENT 12.0 was used to solve the above equations using the pressure based couple solver, SIMPLE (ANSYS FLUENT Theory Guide 2009). Phase couple SIMPLE scheme solves velocity and pressure field simultaneously using least squares cell discretisation technique and based on finite volume method.

Numerical Grid Generation

While a 3D model of SRT clarifier is possible, it is more expensive due to high computation time required. A reasonable degree of simplification was achieved with a 2D axisymmetric model assuming circumferentially continuous outlet and inlet.

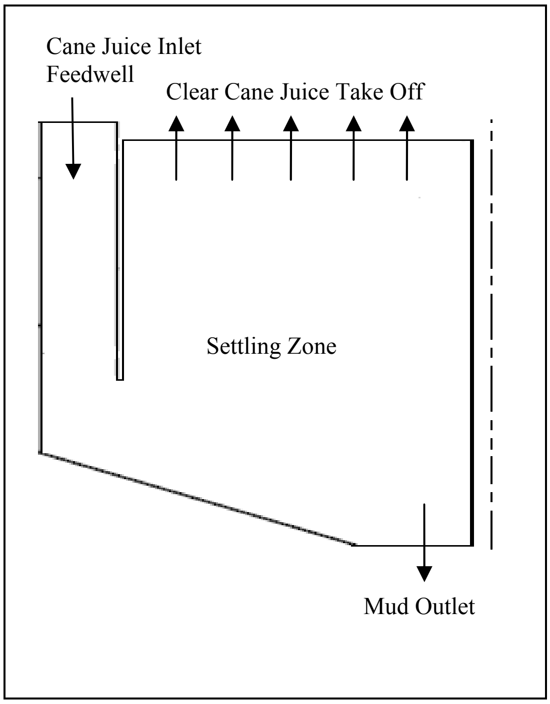


Figure 2: 2D axi-symmetric diagram of SRT clarifier showing inlet feed well, settling zone and clear cane juice take off zone.

The two dimensional geometry of the SRT clarifier is shown in the Figure 2. Dimensions of SRT clarifier are listed in Table 1.

Dimensions	Value (m)
Outside diameter	6.0
Feedwell width	0.5
Feedwell depth	2.5
Mud thickener diameter:	1.5
Settling zone depth	3.0
Cane juice inlet and outlet level difference	0.05

Table 1: Dimensions of SRT clarifier.

Gambit Software was used to model the geometry with an unstructured triangular mesh created. The inlet feed launder and the take off launder are not modelled as they are not axisymmetric. A small pressure drop is produced at the perforated plate near clear take off launder. The perforated plate provides equal opportunities for clear cane juice particles to come out from the clarifier. An effect of the perforated plate is not considered to achieve simplification. The triangular mesh of SRT clarifier has approximately 186,268 cells. A small portion of mesh around inlet feed well is shown in Figure 3.

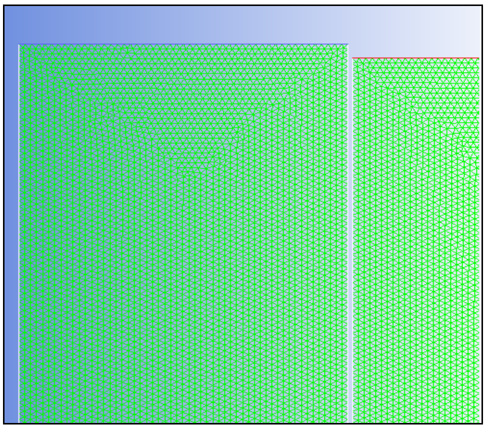


Figure 3: Triangular Mesh around inlet feed well of SRT Clarifier.

Boundary Conditions

Velocity inlet conditions are applied to the inlet surface at the top of the feed well. At the inlet constant profiles for the turbulence kinetic energy and energy dissipation are adopted. Analysis parameters are listed in Table 2.

Parameters	Value
Inlet feed velocity at top of feedwell (m/s)	0.050 to 0.004
Cane juice viscosity (Pa.s)	0.0005
Cane juice density (Kg/m³)	1050
Mud particle density (Kg/m³)	1070
Mud particle diameter (m)	0.001
Volume fraction of mud particles (%)	8

Table 2: Parameters for analysis.

The outlet flow is perpendicular to the boundary. Two outflow boundary conditions have been defined.

- Clear juice from top
- Mud removal from bottom

The axis boundary type is used as the centreline of an axisymmetric geometry. When creating 2D axisymmetric geometry, the axis boundary is lie on the y=0 line i.e. 'X' axis is always axis of symmetry.

Turbulent flows are significantly affected by the presence of walls. The mean velocity field is influenced by the no-slip condition at the wall. However, the turbulence is also altered by the presence of walls in other ways. Very close to the wall, viscous damping reduces the tangential fluctuations, as well as the normal fluctuations. Wall boundary conditions are used to bound fluid and solid regions. Clarification is achieved by natural process of sedimentation. Gravitational acceleration of (-) 9.81 m/s² is applied.

RESULTS

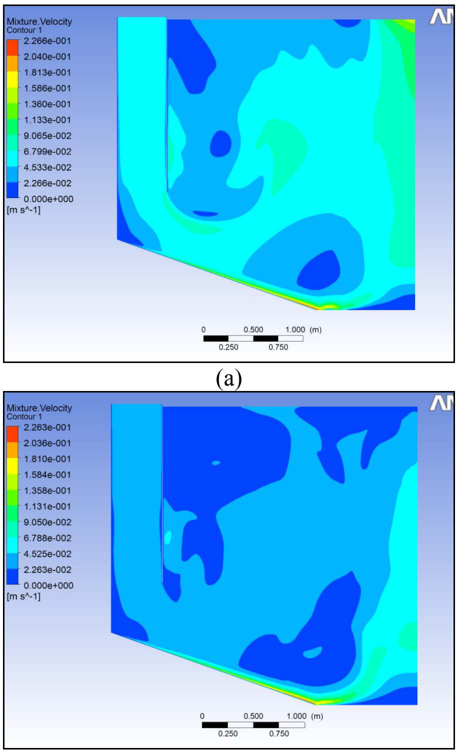
Four inlet feed velocities were modelled to study internal flow fields for operation of the SRT clarifier and are listed in the Table 3.

Inlet feed Velocity (m/s)	Settling Velocity (m/s)	Flow Pattern
0.050	0.040 to 0.050	Large Vortex forming
0.030	0.020 to 0.030	Small Vortex forming
0.010	0.0035 to 0.0045	Uniform Velocity
0.004	0.0015 to 0.0025	Uniform Velocity

Table 3: Model flow conditions and respective settling velocities

Flow patterns in a SRT Clarifier

Ideal flow pattern would be a straight juice path from inlet to outlet allowing sufficient time for mud settling and keeping average residence time low. Ideal velocity in the settling zone is around 0.005 m/s which depends on initial rate of settling (R.J. Steindl, 1995).

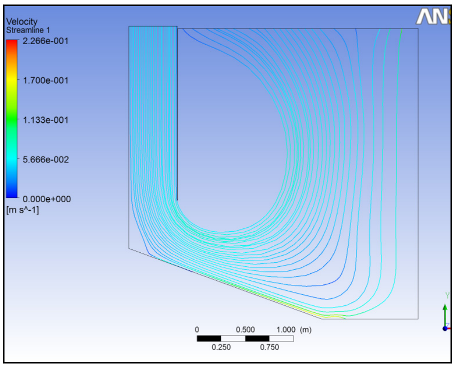


(b)

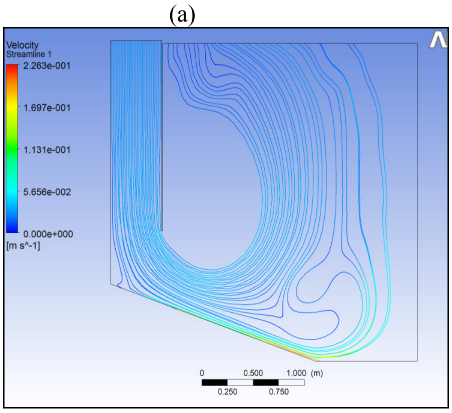
Figure 4: Velocity contour plot for inlet feed velocity (a) 0.050 m/s (b) 0.030 m/s

Velocity contours in the settling zones are not uniform as shows in Figure 4 (a) and (b). Recirculation regions are identified in the settling zone shown in Figure 5 (a) and

(b) and streamline plot indicates flow rates are much higher than required for optimum settling behavior of mud particles. The mud particles fail to settle at settling velocity approaches around 0.040 m/s. the recirculation pattern reduces the effective volume of the clarifier compartment. A higher velocity increases the chances bagacillo particles and small mud particles will carry over with clear cane juice.



(a)



(b)

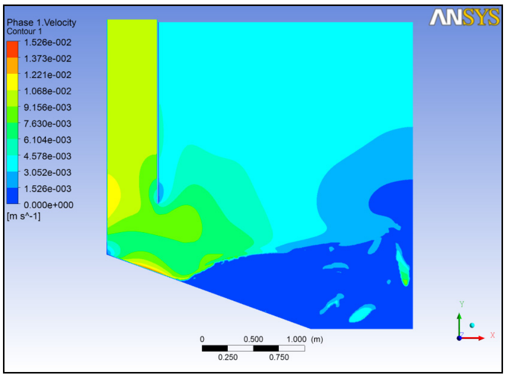
Figure 5: Streamline contour for inlet feed velocity (a) 0.050 m/s and (b) 0.030 m/s.

In the recirculation regions velocity becomes almost zero which affects the capacity of the clarifier. Juice flow rate is a crucial parameter which affects clarity of clear cane juice and capacity of the clarifier. Inlet feed velocities 0.050 m/s and 0.030 m/s are not recommended.

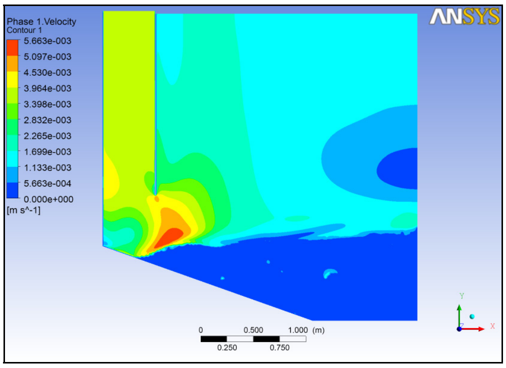
Velocity contours shown in Figure 6 (a) are uniform in the settling zone. Velocity contours shown in Figure 6 (b) indicates an increase in velocity near throat region due to back pressure of settling mud particles and cane juice.

Streamlines shown in Figure(c) indicates no vortex forming and utilized maximum capacity of the clarifier as compare to Figure 5. Vector plot shown in Figure 6(d) also illustrates the maximum utilization of compartment of the clarifier.

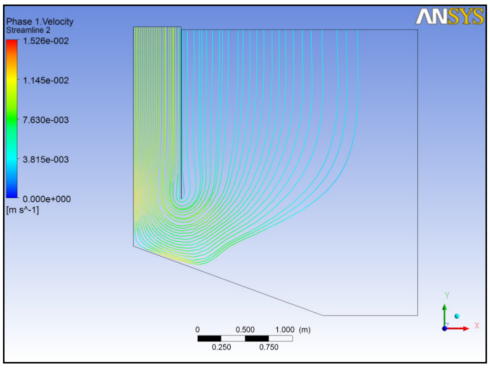
Settling velocity is an important design parameter in clarifier design. Study of flow pattern and settling velocities for four inlet feed velocity conditions suggests that an inlet feed velocity of 0.010 m/s produces optimum capacity utilization of the clarifier which should provide conditions for optimum clear juice clarity.



(a)



(b)



(c)

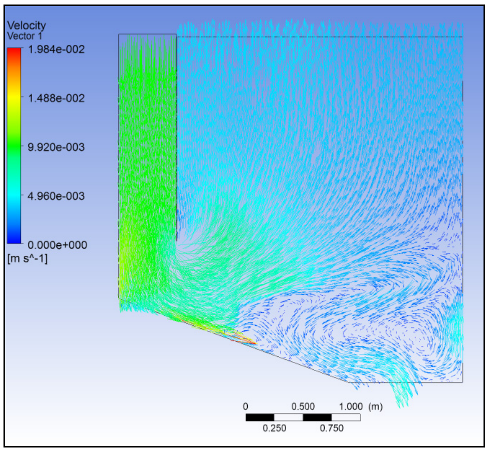


Figure 6: Velocity contour plot for inlet feed velocity (a) 0.010 m/s (b) 0.004 m/s, streamlines contours for inlet feed velocity 0.010 m/s (c) and velocity vectors for inlet feed velocity 0.010 m/s (d).

Volume Fractions

The volume fraction of mud particles in the cane juice at inlet feed launder is 8%. Volume fraction of mud particles for inlet velocity 0.010 m/s is shown in Figure 7. The maximum percentage of mud particles in the clarifier are shown by red colour and blue colour indicates minimum. The interface between maximum and minimum volume fraction is present in the bottom cone of the clarifier and below the settling zone. It indicates the clear interface between cane juice and mud particles. Mud particles move downward to mud thickener.

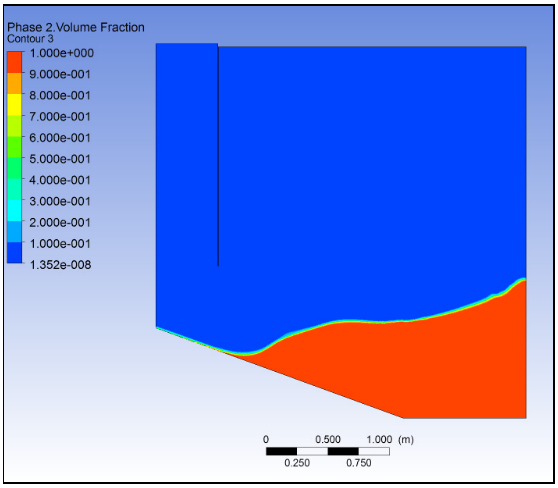


Figure 7: Volume fraction of mud particles for inlet feed velocity 0.010 m/s.

Optimum Flow Rate

Retention time and flow rate are inversely proportional. Optimum flow rate depends upon required settling velocity for effective clarification. Effective clarification at low retention time can be achieved by optimizing the flow rate. The flow rate of inlet feed velocity 0.010 m/s is recommended which produces the most uniform flow field inside the clarifier and effective settlement of mud particles as shown in Figure 8. The retention time depends upon “initial rate of settling”. The average retention time is 20 to 30 minutes and flow rate is 250 m³/h for inlet feed velocity of 0.010 m/s.

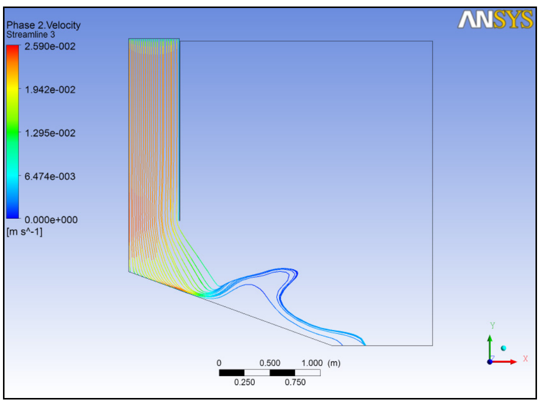


Figure 8: Streamlines of mud particles for inlet feed velocity 0.010m/s.

Sucrose Inversion Loss

The low retention time of the SRT clarifier leads to temperature drop from feed juice to clear juice of 2-3°C. A larger temperature drop is experience in multitray clarifiers due to the excessive retention time, is also linked to sucrose inversion losses as well as reducing the quantity of degradation products that occurs during the clarification process. Sucrose inverted per hour at pH 7.0 and temperature of 100° C is 0.021% (E. Hugot, 1986). Sucrose inversion loss of SRT clarifier is 0.07 % as compared to 0.13 % for conventional multitray clarifiers.

Sucrose inversion is highly sensitive to heat. Less formation of colouring matter occurs in SRT clarifier compared to multitray clarifier designs due to reduced time of heat exposure. More retention time increases the risk of additional colour compounds forming.

Clarity of Clear Cane Juice

The clarity of clear cane juice is measured in terms of turbidity. The turbidity of clarified cane juice from the factory trial conducted at M/s Krishna SSK Sugar factory, Athani, Karnataka, India is in the range of 5 to 10 IU at 900 nm (ICUMSA Method GS7-21, 1974). ICUMSA method measures absorbance of clarified juice due to suspended solid against distilled water in the spectrophotometer at a wavelength of 900 nm where the effect of light absorption is assumed to be zero.

Figure 9 shows more transparent clear cane juice in (right side) as compared to old design (left side).

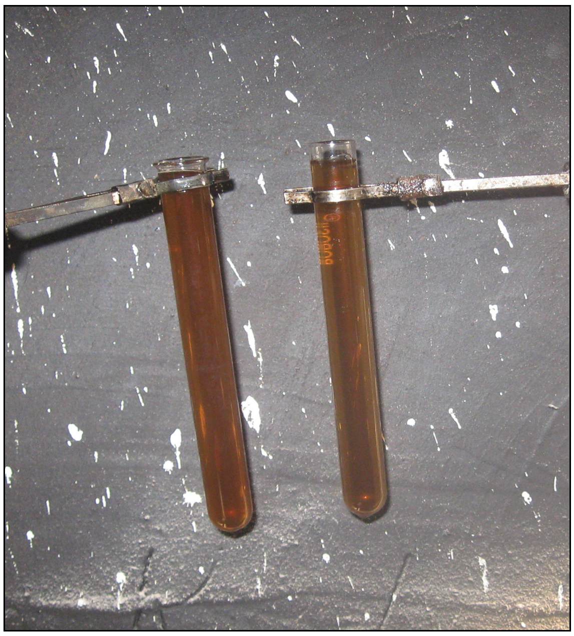


Figure 9: Clear cane juice in test tube for old design (left side) and new design (right side)

Cost Benefits

Due to less juice load and structural weight, the cost of foundation and insulation cladding for SRT clarifiers is significantly less than multitray clarifiers. An additional benefit is the lower factory footprint required by the SRT clarifier.

Flocculent consumption is slightly higher for the SRT clarifier. This additional cost however is balanced against lower sucrose inversion loss.

CONCLUSION

The results of CFD analysis helps to understand the flow pattern of clear cane juice and separated solids inside the clarifier. Recirculation is common problem in clarifier design and creates turbulence in the flow field of the settling zone. CFD analysis assists in determining recirculation regions and settling velocities which are important parameters in the clarifier design. An inlet velocity of 0.010 m/s is recommended which provides optimum cane juice clarity and the desired throughput capacity of the clarifier.

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