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DETERMINING THE MEAN RESIDENCE TIME DISTRIBUTION IN FLOCCULATION ZONE OF JET CLARIFIER BY COMPUTATIONAL FLUID DYNAMICS (CFD) ANALYSIS

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Presentation Outline

Outline

- Introduction
- Global Analysis
  - Turbidity Removal Efficiency
  - Residence Time Distribution (RTD)
- Local Analysis → Simulation
- Conclusion

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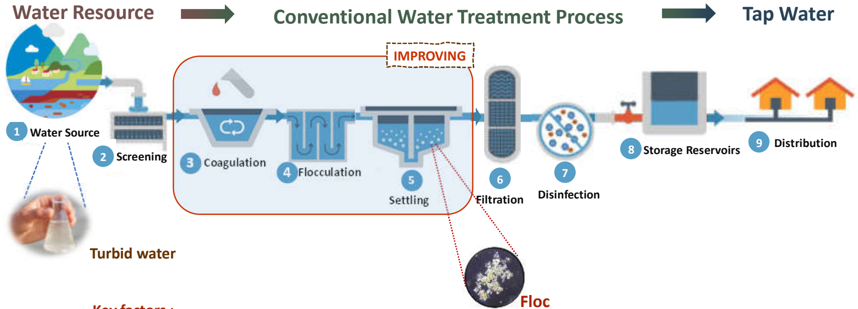
Introduction | Global Analysis | Local Analysis | Conclusion

Water Resource → Conventional Water Treatment Process → Tap Water



The terminal velocity of the flocs relates to density and size

Key factors :

- Velocity Gradient (G)
- Contact Time (t)
- Camp Number (*Gt*)

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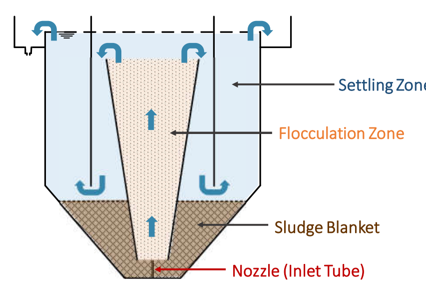
Introduction | Global Analysis | Local Analysis | Conclusion

Jet Clarifier



A Schematic Diagram of Hydrodynamics

Key factors :

- Velocity Gradient (G)
- Contact Time (t)
- Camp Number (*Gt*)

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RESEARCH GAP

- Until now, the **design criteria** concerning jet clarifier has not been studied.
- In order to develop the **design criteria**, the **parameters affecting** the turbidity removal **efficiency** should be comprehensively understood.

OBJECTIVES

- To investigate the sensitivity of turbidity removal efficiency to **liquid flow rate**, **reactor configuration** and liquid **flow pattern** in the jet clarifier
- To determine **velocity gradient** and **contact time** in the jet clarifier

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Turbidity Removal Efficiency

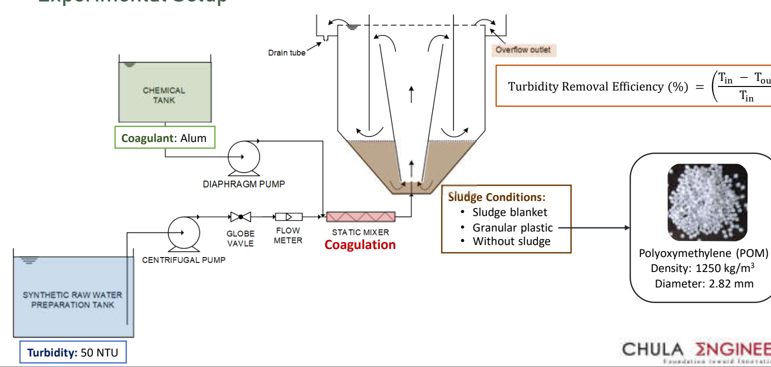
Experimental Setup

Operating Conditions

Operating Conditions	Value(s)
Total volume	
• Large Scale Prototype	243 L.
• Small Scale Prototype	67 L.
Liquid flow rate	
• Large Scale Prototype	40, 70, 180 L/hr.
• Small Scale Prototype	11, 19, 49 L/hr.
Theoretical residence time ($\tau = \frac{V}{Q}$)	
• Existence of sludge	365, 209, 81 min
• Non-existence of sludge	318, 182, 71 min
Diameter of the truncated cone base	
• Large Scale Prototype	5, 10, 15 cm.
• Small Scale Prototype	3, 6.5, 10 cm.

Turbidity Removal Efficiency

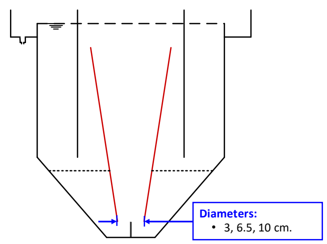
Experimental Setup

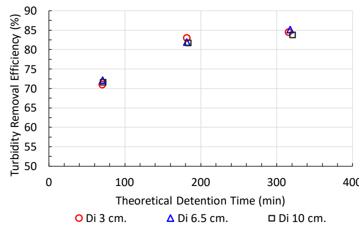


$$\text{Turbidity Removal Efficiency (\%)} = \left(\frac{T_{in} - T_{out}}{T_{in}}\right) \times 100$$

Turbidity Removal Efficiency

Impact of Diameters of the Truncated Cone Base on Turbidity Removal Efficiency



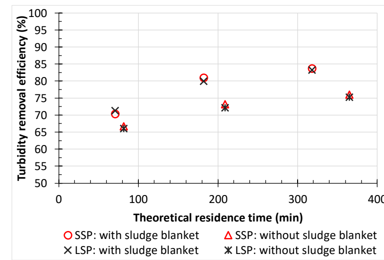


Summary

- Diameters of the truncated cone base do not affect turbidity removal efficiency

Turbidity Removal Efficiency

Effects of Liquid Flow Rate, Reactor Size and Sludge Blanket on Turbidity Removal Efficiency



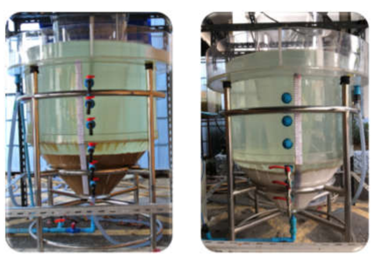
Sludge blanket condition	Theoretical residence time (τ) (min)	Flow rate (L/hr.)		Treatment efficiency at steady state (%)	
		LSP	SSP	LSP	SSP
Without	365	40	11	75.30	76.04
	209	70	19	72.11	73.21
	81	180	49	66.07	66.67
With	318	40	11	83.22	83.68
	182	70	19	80.00	81.03
	71	180	49	71.33	70.32

Summary

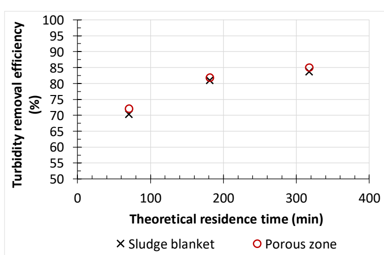
- Sizes of reactors do not affect turbidity removal efficiency
- Liquid flow rate and sludge blanket affect turbidity removal efficiency

Turbidity Removal Efficiency

Effects of Characteristics of Sludge on Turbidity Removal Efficiency



Large Scale Prototype



Summary

- Porous zone mimic correctly the sludge blanket

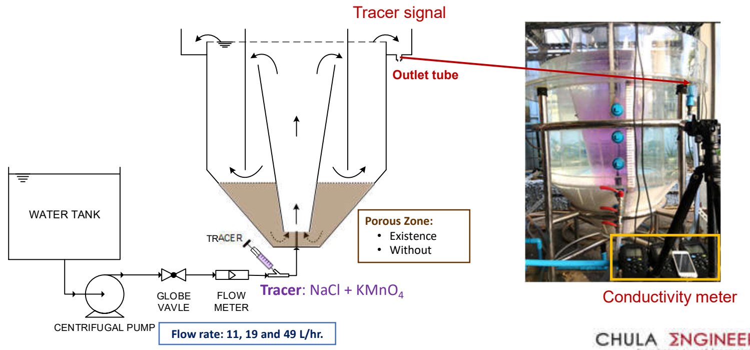
Mean Residence Time Distribution (RTD)

Based on previous results

- RTD study focuses to **sensitivity of liquid flow rate**
  - No sensitivity to internal geometry
  - No expected sensitivity to reactor size
- Porous media will be used to **mimic sludge blanket**

Mean Residence Time Distribution (RTD)

Experimental Setup

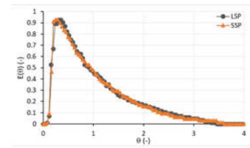


Mean Residence Time Distribution (RTD)

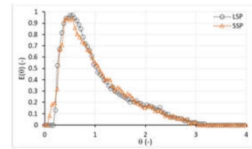
The Effect of Porous Zone and Liquid Flow Rate on Exit Age Distribution

Flow rate: 49 L/hr.

- w/o porous



- with porous



Conditions	Theoretical residence time; τ (min)	Mean residence time; t_m (min) SSP	LSP
without porous	365	305	315
	209	200	197
	81	72	73
with porous	318	290	286
	182	159	161
	71	63	65

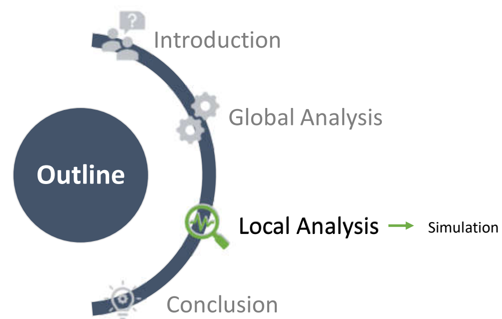
Summary

- The liquid flow rate and porous zone affect the mean residence time (t_m)

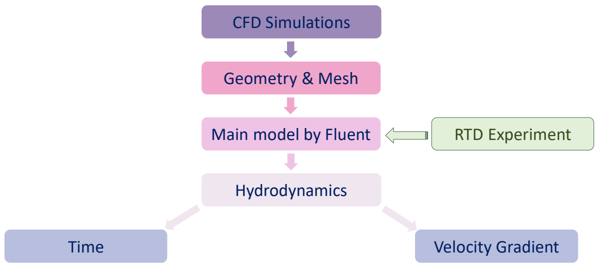
Global Analysis Conclusion

- Both **turbidity removal efficiency** and **mean residence time** of the jet clarifier are **sensitive to the liquid flow rates and the sludge blanket**
- Need to better understand the **mechanism controlling** turbidity removal efficiency of the jet clarifier; topics addressed in the next part are
  - Local analysis of the **hydrodynamics**
- Upscaling issues
  - Based on **CFD**; addressed in the last part

Presentation Outline



Overall Framework of Simulation



- RTD Simulation
- Internal Age

Computational Fluid Dynamics (CFD)

- The **objective** is to **reproduce hydrodynamics** phenomena of SSP in order to **consider upscaling** based on CFD
- Solving the CFD Simulation on ANSYS FLUENT
  - The geometry used to reproduce hydrodynamics is SSP
  - The **models** are chosen to solve the CFD:
    - **Laminar flow**
    - **Turbulence flow**: (1) Standard k-ε
      (2) Detached Eddy Simulation (DES)
  - Passive Scalar Transport for RTD-numerical
  - Species Transport for Internal Age Distribution Simulation

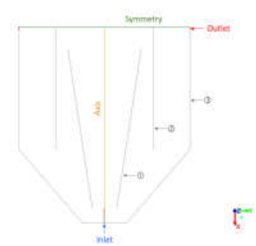
Computational Fluid Dynamics (CFD)

Setting Up the CFD Simulation on ANSYS FLUENT

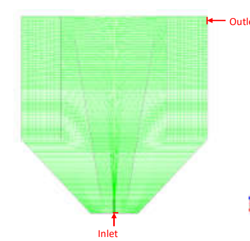
- **Dimension :** 2D, Axisymmetric
- **Model**: (1) Laminar
  (2) Standard k-ε
  (3) Detached Eddy Simulation (DES)
- **Boundary Conditions**
  - **Velocity-inlet:** (1) 0.2554 m/s
    (2) 0.4467 m/s
    (3) 1.1489 m/s
- **Transient Calculation:**
  - **Time Step Size:** 0.001 s

Pre-processing : Geometry and Mesh

3D SSP jet clarifier



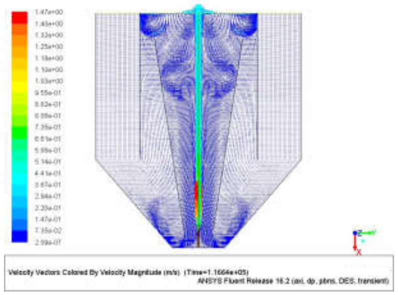
2D Geometry of the jet clarifier



Mesh size of the jet clarifier
(near 19000 nodes)

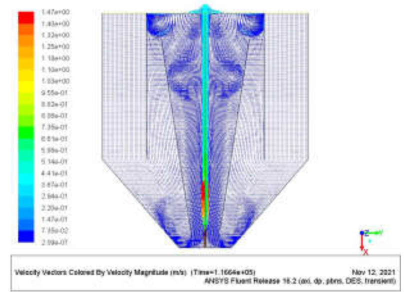
Results: Velocity Flow Field

Conditions:
- 2D Axisymmetric case
- 49 L/hr. flow rate

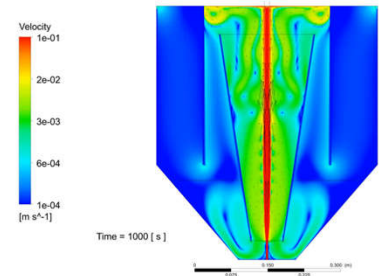


Results: Velocity Flow Field

Conditions:
- 2D Axisymmetric case
- 49 L/hr. flow rate

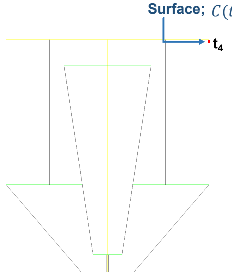


Contour of velocity (transient DES)



Numerical RTD and Tracer Concentration Tracking Position

Surface; $C(t) = \frac{\int_0^n C(x,y,z,t)dS}{S}$



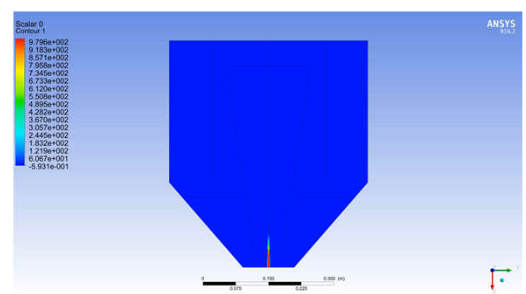
Geometry of the jet clarifier

Transient species transportation

- $\frac{\partial C_t}{\partial t} + \nabla\cdot(\vec{U_i}\, C) = \nabla\cdot\,(D_{ef}\,\nabla C)$
- $\frac{\partial \bar{C}}{\partial t} + \nabla\cdot(\bar{\vec{U_i}}\,\bar{C}) = \nabla\cdot\,\left(D_{ef}\,\nabla\bar{C} - \overline{u_j c}\right)$

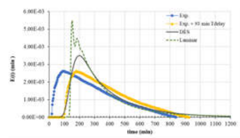
Contour of Scalar (Passive Scalar Transport for RTD-numerical, transient)

Conditions:
- 2D case
- 49 L/hr. flow rate

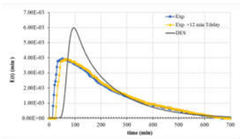


The RTD Curves

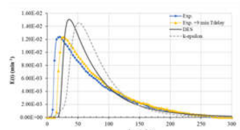
11 L/hr.



19 L/hr.



49 L/hr.



Mean residence time distribution of the SSP from numerical and adjusted experimental data

Flow rate (L/hr.)	Method	t_{10} (min)	t_m (min)	Std. Deviation, σ (min)	Skewness, s^3 (-)
11	Experiment	159	365	180	0.71
	Numerical (DES model)	163	369	164	0.97
19	Experiment	60	210	139	0.91
	Numerical (DES model)	85	204	123	1.28
49	Experiment	27	81	54	1.10
	Numerical (DES model)	32	78	48	1.45

Summary

- The delay is adjusted to have the same mean residence time experimentally and theoretically.

Internal Age Method and Local Camp Number

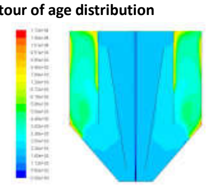
- Scalar 0 → Age ; $\nabla \cdot (\vec{U_i} A) = \nabla \cdot (D_{ef} \nabla A) + 1$
- Scalar 1 → σ^2 ; $\nabla \cdot (\vec{U_i} M_2) = \nabla \cdot (D_{ef} \nabla M_2) + 2A$
- Scalar 2 → Skewness ; $\nabla \cdot (\vec{U_i} M_3) = \nabla \cdot (D_{ef} \nabla M_3) + 3\sigma^2$
- Scalar 4 → $G_{total} \times t$; $\nabla \cdot (\vec{U_i} M_4) = \nabla \cdot (D_{ef} \nabla M_4) + G$

Mean Age Distribution in Jet Clarifier

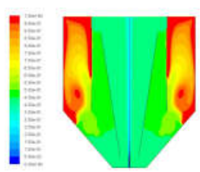
Mean residence time of SSP by DES model

Theoretical residence time (min)	Mean residence time distribution (min)		Std. deviation, σ (min)		Skewness, s^3 (-)	
	Simulation method		Simulation method		Simulation method	
	RTD-numerical	Internal age at the outlet (M_1)	RTD-numerical	Std (M_2) at the outlet	RTD-numerical	M_3 at the outlet
365	369	364	164	222	0.97	1.69
209	204	209	123	146	1.28	1.96
81	78	81	48	53	1.45	2.89

Contour of age distribution



time (s), 49 L/hr.



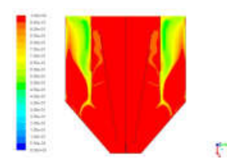
non-dimensional time (θ), 49 L/hr.

Mean Age Distribution in Jet Clarifier

- **The residence time of flocculation zone by species transport for internal age distribution simulation**

Injected flow rate (L/hr.)	The mean resident time of flocculation zone (min)		Standard deviation (σ) (min)	Ratio of Internal age/ Theoretical time
	Theoretical time (t)	Internal age		
11	33.2	204	205	6
19	19.0	118	124	6
49	7.4	40	40	6

- **The distribution of the normalized variance** (CoV=$\sqrt{\sigma^2/\tau^2}$)



Contour of normalized variance of the SSP

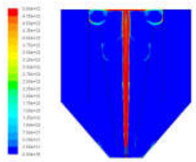
Summary

- The character of the flow pattern of the SSP is perfectly mixed flow (CoV = 1) following by plug flow (CoV = 0)
- In the flocculation zone, the mean residence time is equal to the standard deviation → perfectly mixed.

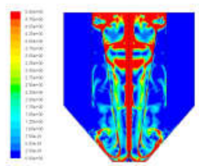
Velocity Gradient (G)

Contours of velocity gradient (G) of 49 L/hr. flow rate

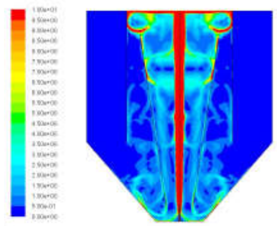
- $G_{meanflow} = \sqrt{\bar{\dot{\gamma}}^2}$ = 3.45 s^{-}



- $G_{turb} = \sqrt{\frac{\varepsilon'}{\nu}}$ = 4.46 s^{-}



- $G_{total} = \sqrt{\bar{\dot{\gamma}}^2 + \frac{\varepsilon'}{\nu}}$ = 6.21 s^{-}



Estimation of Mixing Parameter in Flocculation Zone of SSP, Based on Fluent

Processed hydrodynamic characteristics for the 3 flow rates of the SSP

Abbreviations	Parameters	Injected flow rate (Q) (L/hr.)		
		11	19	49
U (m/s)	Injection velocity	0.24	0.42	1.08
t_{RF} (min)	Residence time in flocculation zone	204	118	40
Q_c (L/hr.)	Circulation flow rate	73	141	338
Q_c/Q	Ratio of circulation flow rate and injected flow rate	7	7	7
t_c (min)	Circulation time	29.1	16.9	5.7
G (s^{-1})	Average value of velocity gradient	0.73	1.55	6.21
Gt (-)	Camp Number of the flocculation zone	4210	4851	7390
$\langle G_{local} \rangle \times \tau$ (-)	Camp Number of the whole reactor	16,000	19,400	30,200

Presentation Outline

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The appropriate conditions in terms of turbidity removal efficiency of the jet clarifier

- The **liquid flow rates** and the **sludge blanket** are the **high impact factors** of the design and operation due to their effects on efficiency.
- **Tank's configuration** has **less impact** on the turbidity removal efficiency.

Hydrodynamics of the jet clarifier

- The jet in the flocculation zone generates a **large circulation loop**.
- The **Camp number remain constant**.
- First simulations based on **CFD** were performed to **compare RTD curves in order to achieve scale-up**

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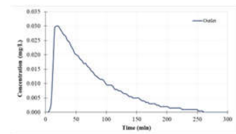
Introduction | Global Analysis | Local Analysis | Computational fluid dynamics | Conclusion

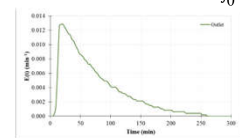
Mean Residence Time Distribution (RTD)

Analytical Methods

- The concentration of tracer VS time



- The fraction of material: $E(t) = \dfrac{C_{(t)}}{\int_0^{\infty} C_{(t)} dt}$



- Mean residence time distribution: $t_m = \dfrac{\int_0^{\infty} tE_{(t)}\, dt}{\int_0^{\infty} E_{(t)}\, dt} = \int_0^{\infty} t\, E(t)\, dt$

- Normalized time: $\theta = \dfrac{t}{\tau}$

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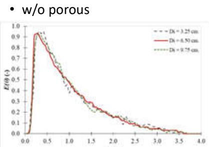
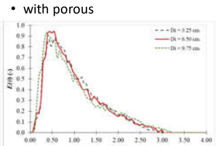
Mean Residence Time Distribution (RTD)

The effect of tank configuration on RTD

Flow rate: 49 L/hr.

- w/o porous
- with porous





Porous	Flow rate (L/hr.)	Diameter (cm.)	Theoretical residence time (min)	t_m (min)	Std. deviation; σ (min)
without	11	3.25	365	302	178
		6.50	365	305	178
		9.75	365	300	187
	19	3.25	209	198	155
		6.50	209	200	143
		9.75	209	196	152
	49	3.25	81	73	47
		6.50	81	72	52
		9.75	81	76	41
with	11	3.25	318	293	162
		6.50	318	290	155
		9.75	318	287	177
	19	3.25	182	165	100
		6.50	182	159	92
		9.75	182	160	88
	49	3.25	71	64	37
		6.50	71	63	36
		9.75	71	65	39

Summary

- The diameters of the truncated cone base do not affect mean residence time distribution (t_m)
- The porous zone affect mean residence time distribution (t_m)

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Introduction | Global Analysis | Local Analysis | Computational fluid dynamics | Conclusion

Setting Up the CFD Simulation on ANSYS FLUENT

- **Dimension :** 2D, Axisymmetric
- **Model**: (1) Laminar (2) Standard k-ε (3) Detached Eddy Simulation (DES)
  - RANS Model → SST k-omega
  - K-omega Options → Low-Re Correction
  - DES Options → Delayed DES
- **General**
  - **Type:** Pressure-Based
  - **Velocity Formulation:** Absolute
  - **Time:** Transient
  - **Gravity:** Gravitational Acceleration x-axis = -9.81 (m/s^2)

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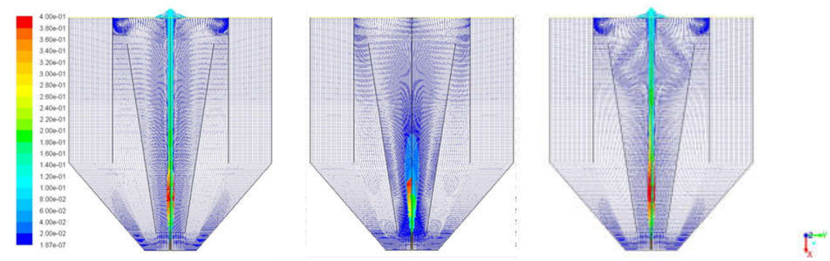
Setting Up the CFD Simulation on ANSYS FLUENT

- **Materials**
  - Water-liquid
- **Cell Zone Conditions:** Fluid
- **Boundary Conditions**
  - **Velocity-inlet:**
    - Small size: (1) 0.2554 m/s (2) 0.4467 m/s (3) 1.1489 m/s (10.99, 19.22, and 49.43 L/hr.)
  - **Outflow:** Flow Rate Weighting 1
- **Solution methods:** Coupled
- **Run Calculation:**
  - **Time Step Size:** 0.001 s

Results: Velocity Flow Field (m/s) of 11 L/hr.



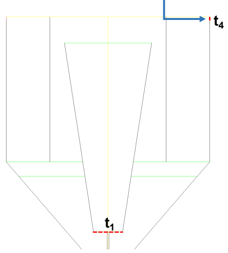
Laminar model | Standard k-ε model | DES model

Numerical RTD and Tracer concentration tracking position

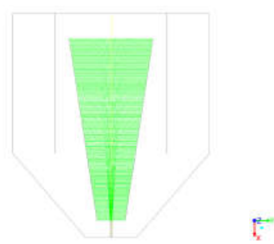
$$\frac{\partial C_t}{\partial t} + \nabla\cdot(\overrightarrow{U_i}\, C) = \nabla\cdot\left(D_{ef}\nabla C\right)$$

$$\frac{\partial \bar{C}}{\partial t} + \nabla\cdot(\overrightarrow{U_i}\, \bar{C}) = \nabla\cdot\left(D_{ef}\nabla \bar{C} - \overline{u_j c}\right)$$

Surface; $C(t) = \frac{\int_0^n C(x,y,z,t)dS}{S}$



Geometry of the jet clarifier

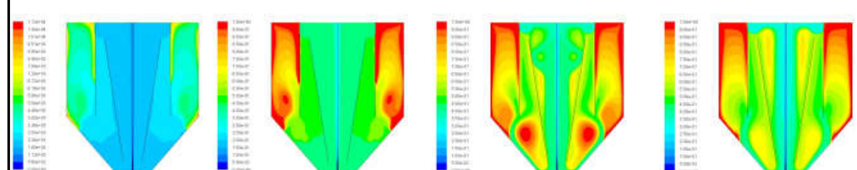


A flocculation zone inside the jet clarifier

Mean residence time of SSP by DES model

Theoretical residence time (min)	Mean residence time distribution (min)		Std. deviation, σ (min)		Skewness, s^3 (-)	
	Simulation method		Simulation method		Simulation method	
	RTD-numerical	Internal age at the outlet (M_1)	RTD-numerical	Std (M_2) at the outlet	RTD-numerical	M_3 at the outlet
365	369	364	164	222	0.97	1.69
209	204	209	123	146	1.28	1.96
81	78	81	48	53	1.45	2.89

Contour of age distribution

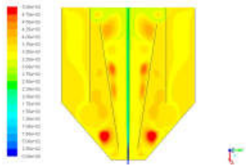


time (s), 49 L/hr. | non-dimensional time (θ), 49 L/hr. | non-dimensional time (θ), 19 L/hr. | non-dimensional time (θ), 11 L/hr.

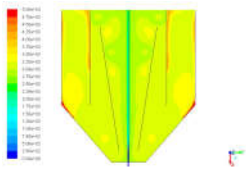
Velocity gradient (G)

Contours of <Gt> of 49 L/hr. flow rate

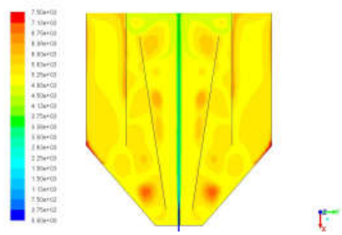
- $G_{meanflow} = \sqrt{\bar{\gamma}^2}$



- $G_{turb} = \sqrt{\frac{\varepsilon'}{\nu}}$



- $G_{total} = \sqrt{\bar{\gamma}^2 + \frac{\varepsilon'}{\nu}}$



Details of experimental set-up

LSP		SSP		Theoretical residence time (min)	
Flow rate (LPH)	Re number	Flow rate (LPH)	Re number	Without porous	With porous
40	2358	**11**	997	365	318
70	4126	**19**	1743	209	182
180	10610	**49**	4483	81	71