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A Computational Fluid Dynamics Study of Fluid Catalytic Cracking Cyclones

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Fluidized Catalytic Cracking (FCC)

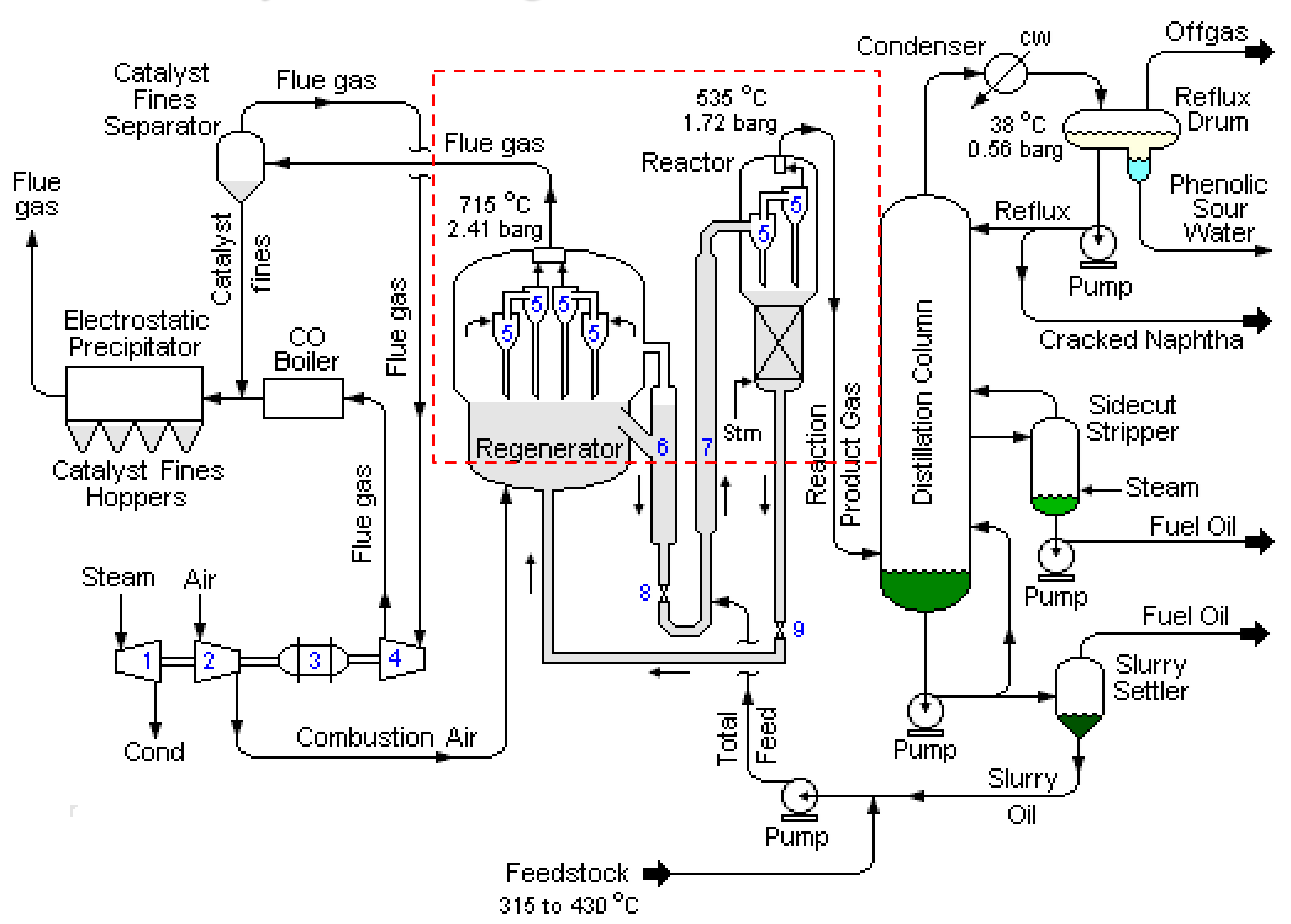
Reactor

- Vaporized oil feedstock is exposed to a catalyst heated to approximately 1,000 deg F - causing the cracking reaction.
- Usually takes place in a riser pipe
- **Cyclones are used to separate the reacted oil feedstock from the catalyst.**
- Reaction is endothermic.

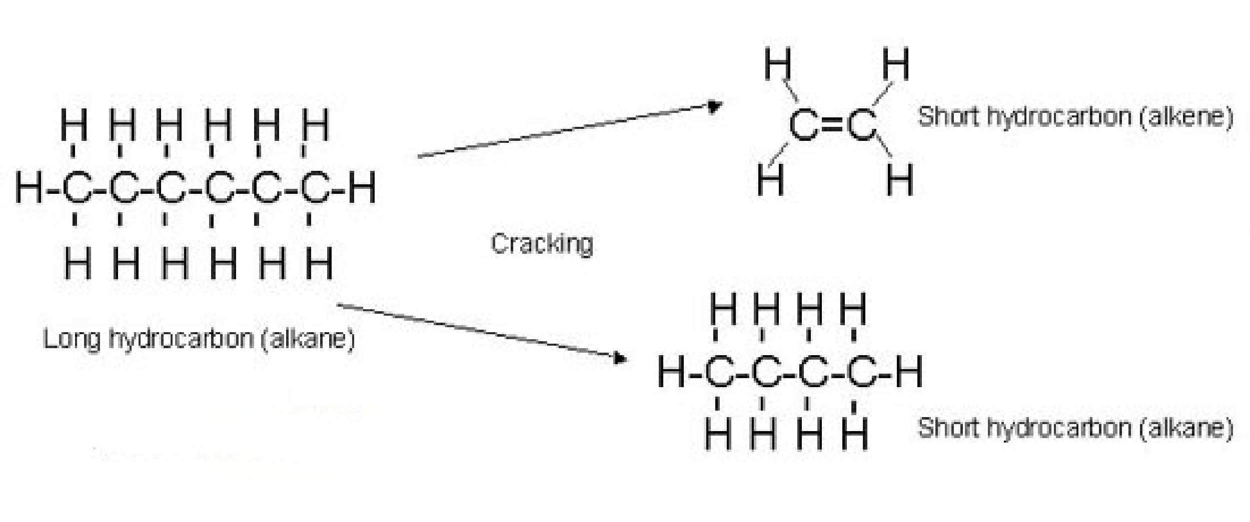
Regenerator

- Coke is built up on the catalyst during the reaction.
- The catalyst is exposed to oxygen in the regenerator igniting combustion.
- The catalyst is “regenerated” by the combustion of the coke.
- **Cyclones are used to separate the catalyst from the flue gas.**
- Reaction is exothermic.

FCC Refinery Flow Diagram



Chemisty of Cracking

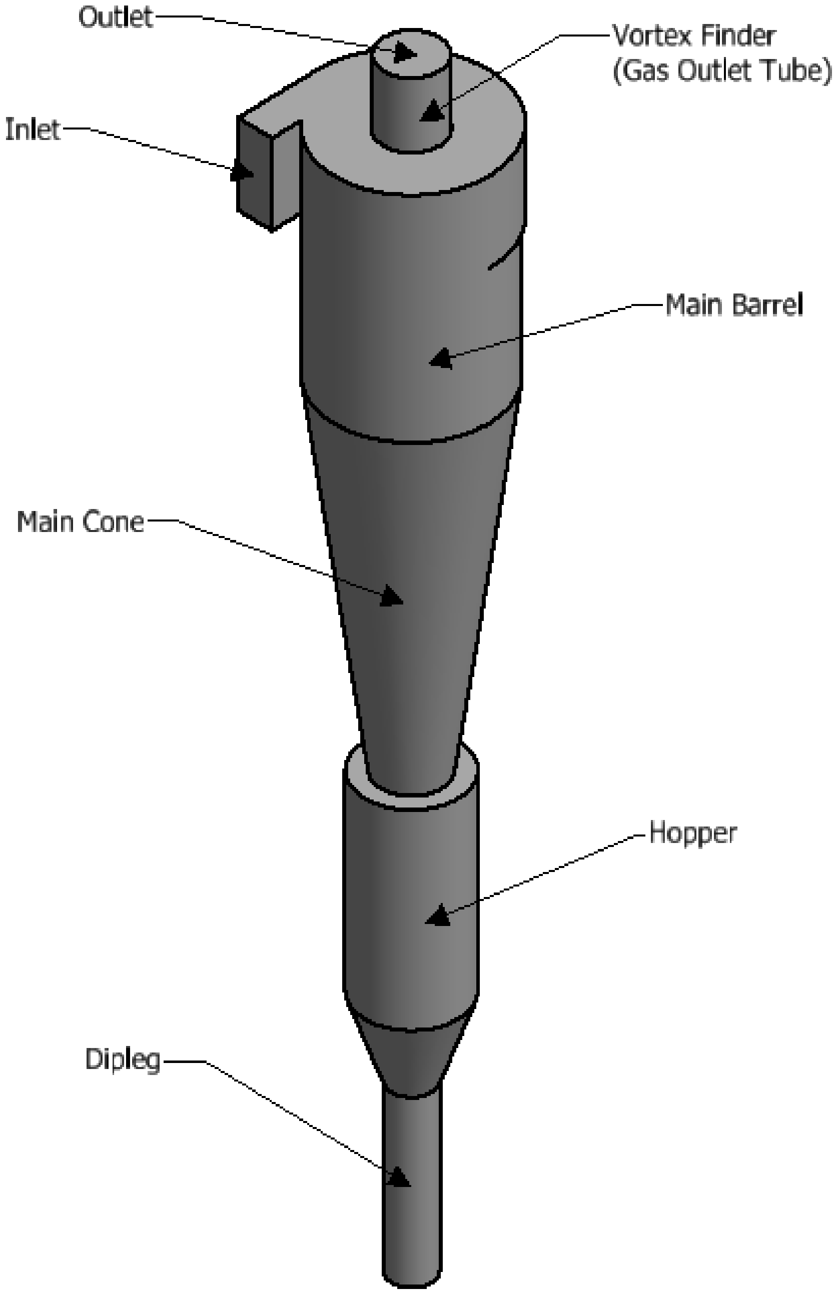


- Alkanes (paraffins) are long chain single bonded hydrocarbons.
- Cracking breaks the long chain into usable short chain alkanes and alkenes.
    - alkanes used for gasoline and fuel oil
    - alkenes have a double covalent bond: ethanol, alcohol, and plastics

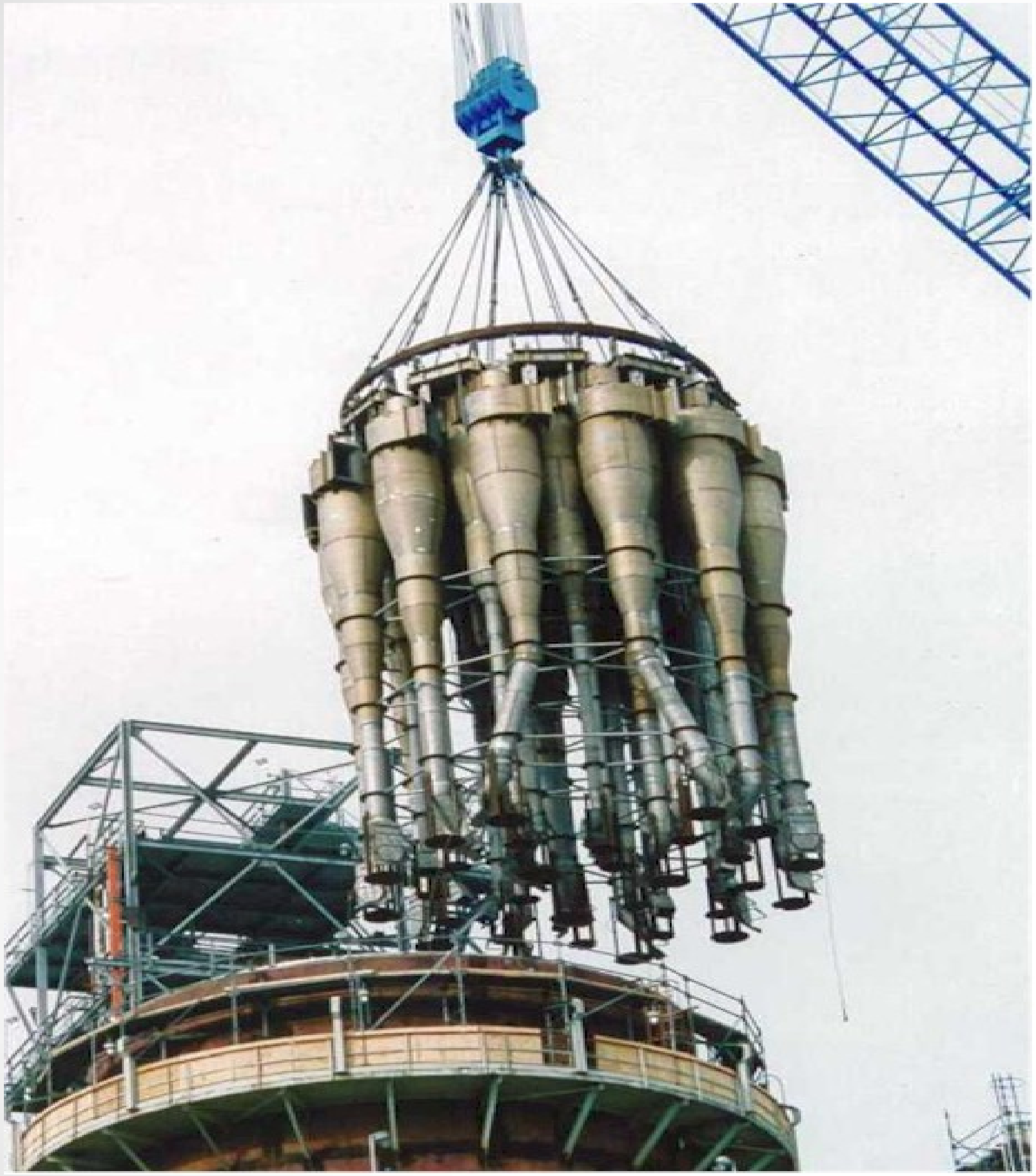
Reactor and Regenerator

- Considered the heart of a refinery.
- Reactor and Regenerator are thermally balanced.
  - heat generated from the exothermic reaction in the regenerator, supplies the endothermic reaction in the reactor.
- Catalyst used to facilitate the reaction is expensive and abrasive.
- Shutdowns are required to repair cyclone lining from erosion.

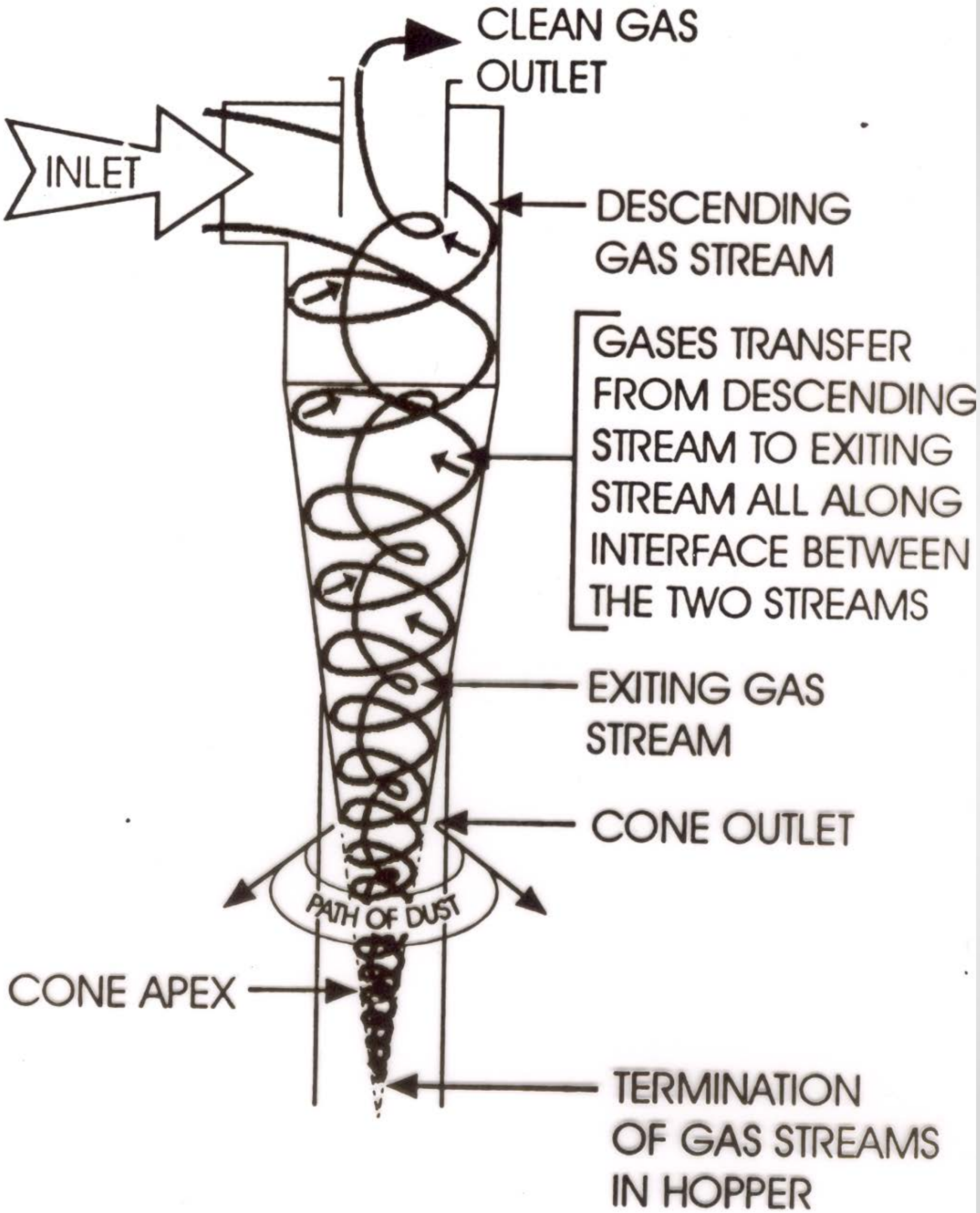
Cyclone Nomenclature



FCC Cyclone Installation



Cyclone Basics



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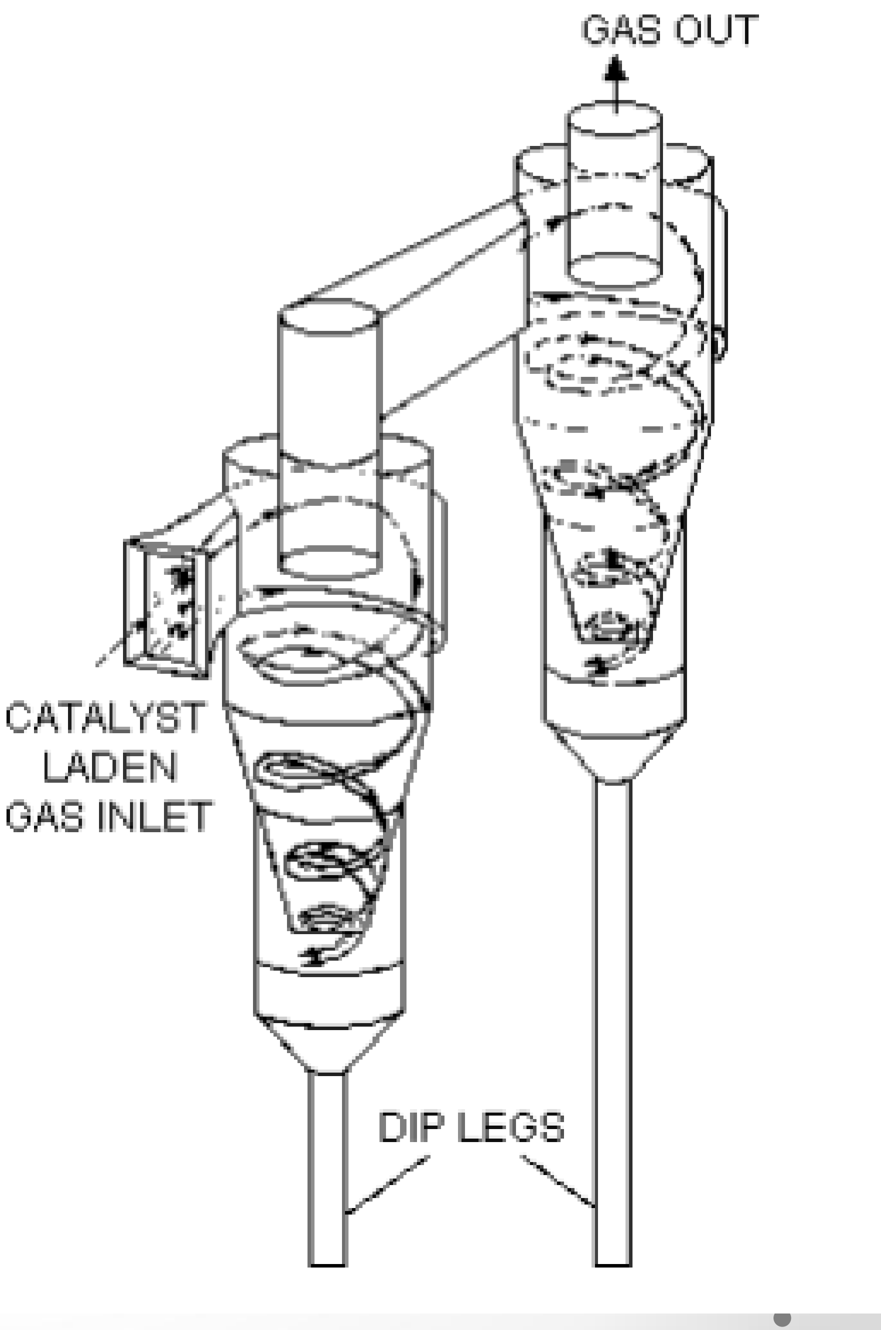
2 Stage Cyclone System

Dense Flow Cyclones (High Mass Loading)

- Large quantities of particulate enter the cyclone.
- 1st Stage Cyclone.

Dilute Flow Cyclones (Low Mass Loading)

- Loading is approximately 5% of a dense flow cyclone.
- 2nd Stage Cyclone



Three Major Parameters of Cyclone Performance

1. **Efficiency**
   - Percent of particles captured of the particles that enter.
   - Typical ranges from 95% to 99%.
2. **Pressure Drop**
   - Pressure loss due to cyclone operation.
   - Cost to operate system.
3. **Erosion**
   - Catalyst is highly abrasive.
   - Maintenance costs.
   - Downtime.

Methods of Cyclone Design

1) **Laboratory Modeling**

2) **Algebraic Equations**

3) **Computational Fluid Dynamics (CFD)**

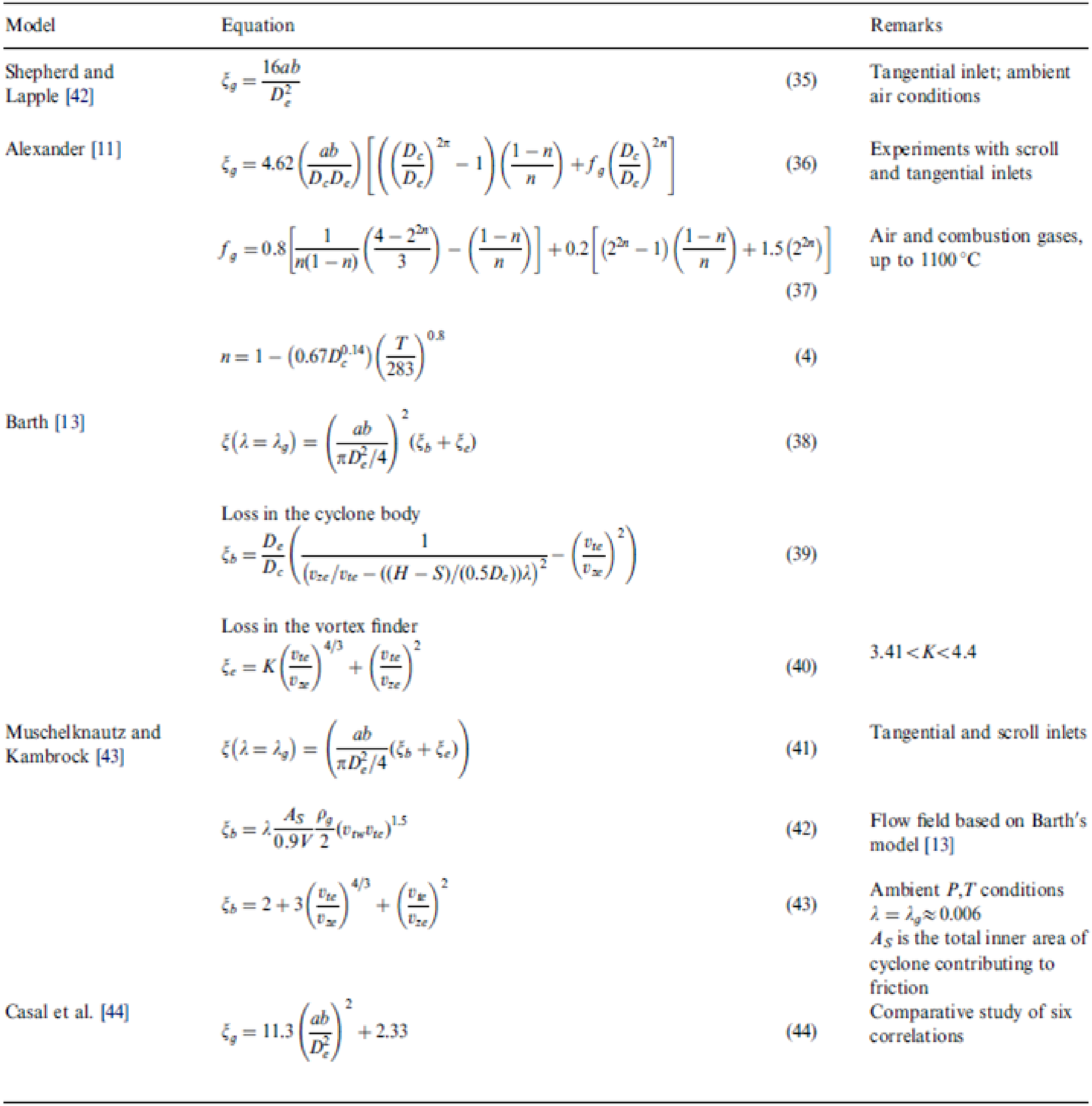
Laboratory Modeling

- Laboratory modeling and empirical testing have been the major methods for developing cyclone technology.

- Scale models were created and results verified by industrial performance.
  - Particulate tests
  - Pressure Loss
  - Erosion

Algebraic Models

- Developed from empirical data.
- Rigid equations that can only be used for narrow applications.



Model	Equation		Remarks
Shepherd and Lapple [42]	$\xi_g = \frac{16ab}{D_e^2}$	(35)	Tangential inlet; ambient air conditions
Alexander [11]	$\xi_g = 4.62\left(\frac{ab}{D_c D_e}\right)\left[\left(\left(\frac{D_c}{D_e}\right)^{2n} - 1\right)\left(\frac{1-n}{n}\right) + f_g\left(\frac{D_c}{D_e}\right)^{2n}\right]$	(36)	Experiments with scroll and tangential inlets
	$f_g = 0.8\left[\frac{1}{n(1-n)}\left(\frac{4-2^{2n}}{3}\right) - \left(\frac{1-n}{n}\right)\right] + 0.2\left[(2^{2n}-1)\left(\frac{1-n}{n}\right) + 1.5(2^{2n})\right]$	(37)	Air and combustion gases, up to 1100 °C
	$n = 1 - (0.67 D_c^{0.14})\left(\frac{T}{283}\right)^{0.8}$	(4)	
Barth [13]	$\xi(\lambda = \lambda_g) = \left(\frac{ab}{\pi D_e^2/4}\right)^2 (\xi_b + \xi_e)$	(38)	
	Loss in the cyclone body $\xi_b = \frac{D_e}{D_c}\left(\frac{1}{(v_{ze}/v_{te} - ((H-S)/(0.5D_e))\lambda)^2} - \left(\frac{v_{te}}{v_{ze}}\right)^2\right)$	(39)	
	Loss in the vortex finder $\xi_e = K\left(\frac{v_{te}}{v_{ze}}\right)^{4/3} + \left(\frac{v_{te}}{v_{ze}}\right)^2$	(40)	$3.41 < K < 4.4$
Muschelknautz and Kambrock [43]	$\xi(\lambda = \lambda_g) = \left(\frac{ab}{\pi D_e^2/4}(\xi_b + \xi_e)\right)$	(41)	Tangential and scroll inlets
	$\xi_b = \lambda \frac{A_S}{0.9V}\frac{\rho_g}{2}(v_{tw}v_{te})^{1.5}$	(42)	Flow field based on Barth's model [13]
	$\xi_b = 2 + 3\left(\frac{v_{te}}{v_{ze}}\right)^{4/3} + \left(\frac{v_{te}}{v_{ze}}\right)^2$	(43)	Ambient P,T conditions $\lambda = \lambda_g \approx 0.006$ A_S is the total inner area of cyclone contributing to friction
Casal et al. [44]	$\xi_g = 11.3\left(\frac{ab}{D_e^2}\right)^2 + 2.33$	(44)	Comparative study of six correlations

Computation Fluid Dynamics (CFD) Models

- Flow is represented by the Navier-Stokes equation.
  - Coupled differential equations that must be solved simultaneously.
- The Navier-Stokes equation is not closed for turbulent flow.
  - Approximations, averages, and constants from testing are used to solve the equations for turbulent flow.

Turbulent Flow Models

1. **k-ε**
   - k – turbulent kinetic energy
   - ε - dissipation rate of k
   - Assumes isotropic turbulence
   - Fast and consistent convergence

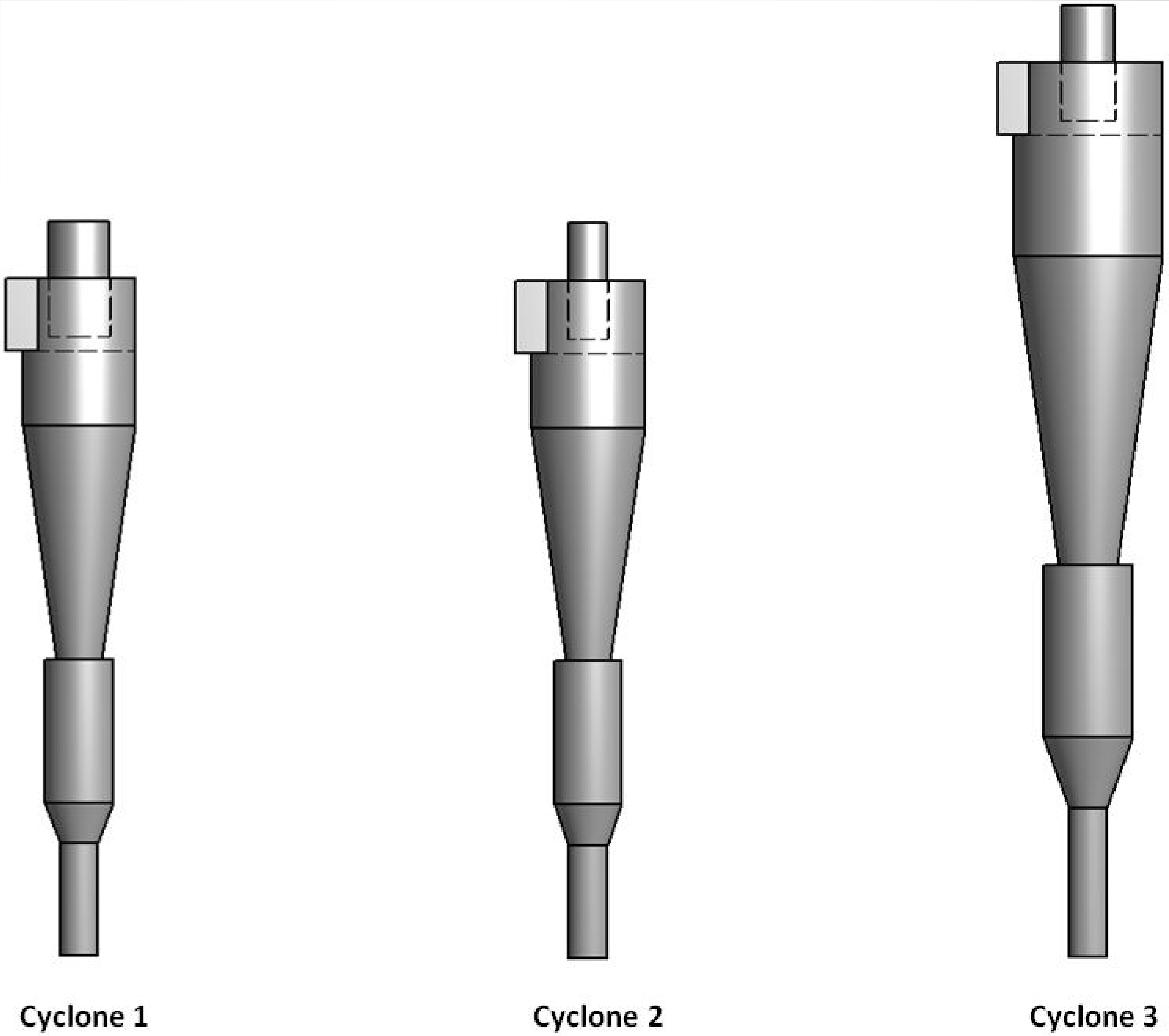
2. **Re**n**ormalized** **G**roup (**RNG**) **k-ε**
   - Adds an additional variable to the standard k-ε model

Turbulent Flow Models

3. **R**eynolds **S**tress **M**odel (RSM)
    - Incorporates transport equations for each Reynolds stress dissipation component
    - Forgoes isotropic turbulence assumption
    - 7 equations
    - High computation costs

4. **L**arge **E**ddy **S**imulation (LES)
    - Transient

Cyclones



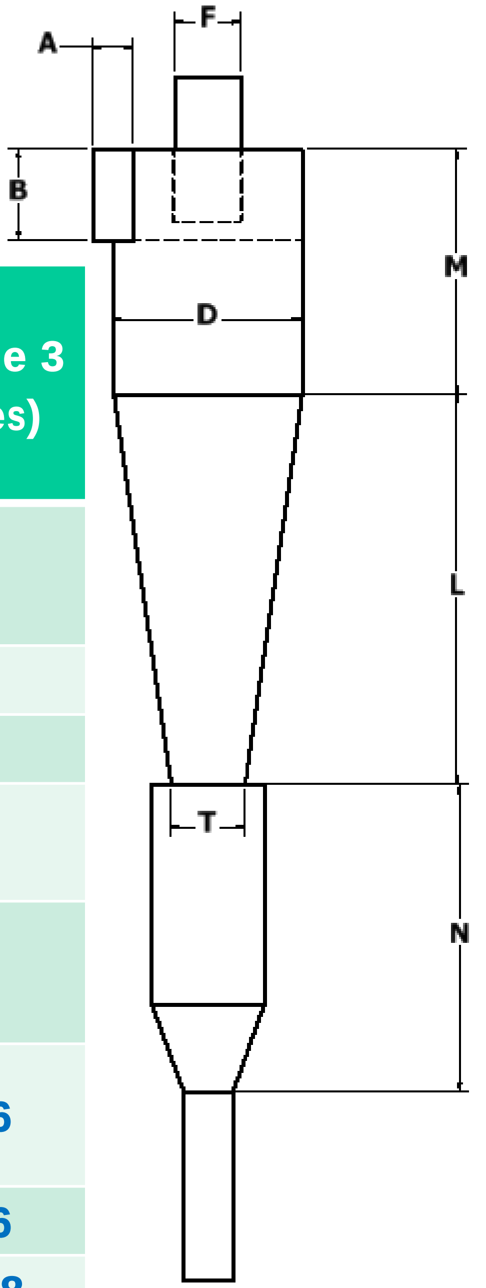
standard design

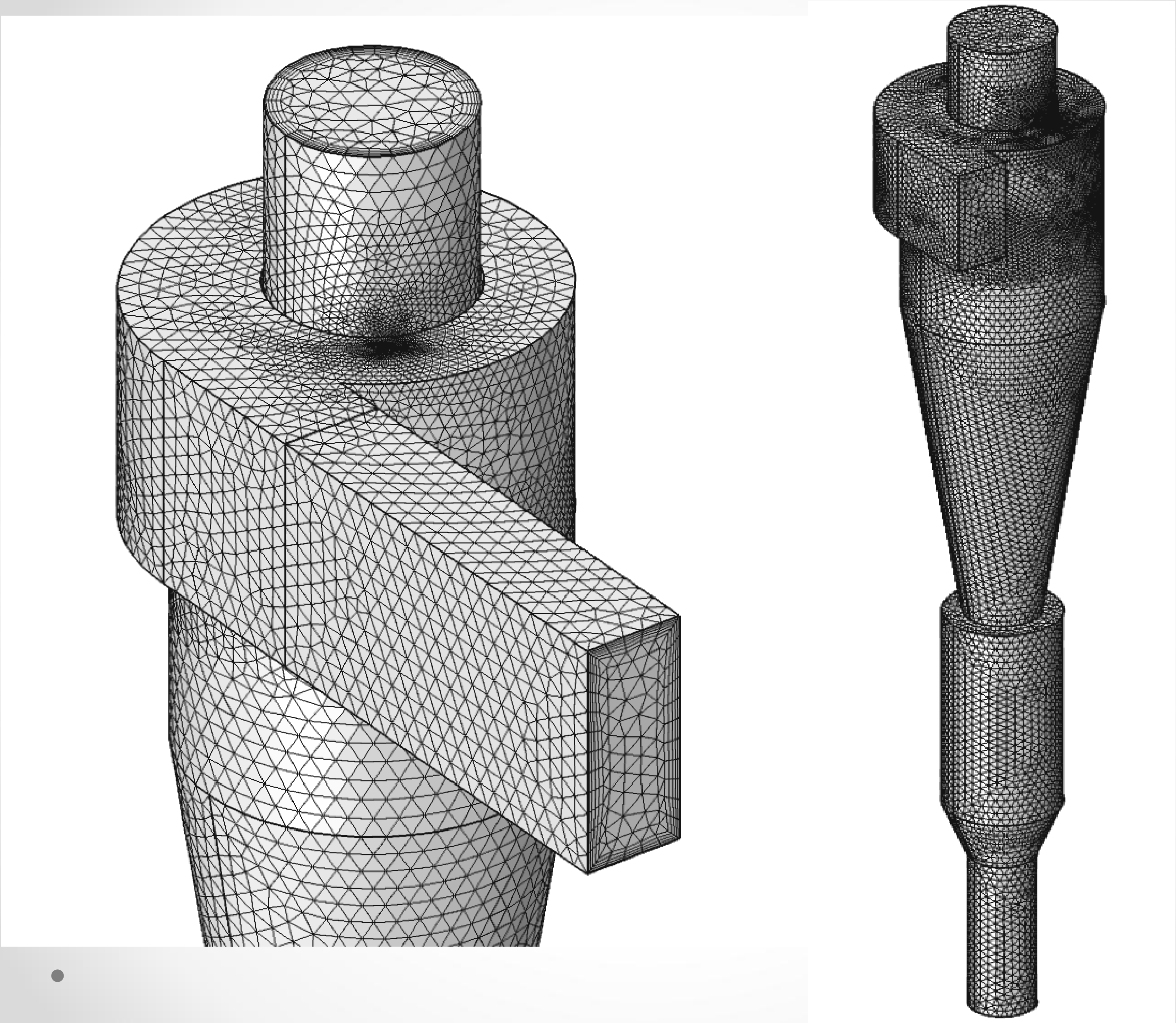
modified outlet tube

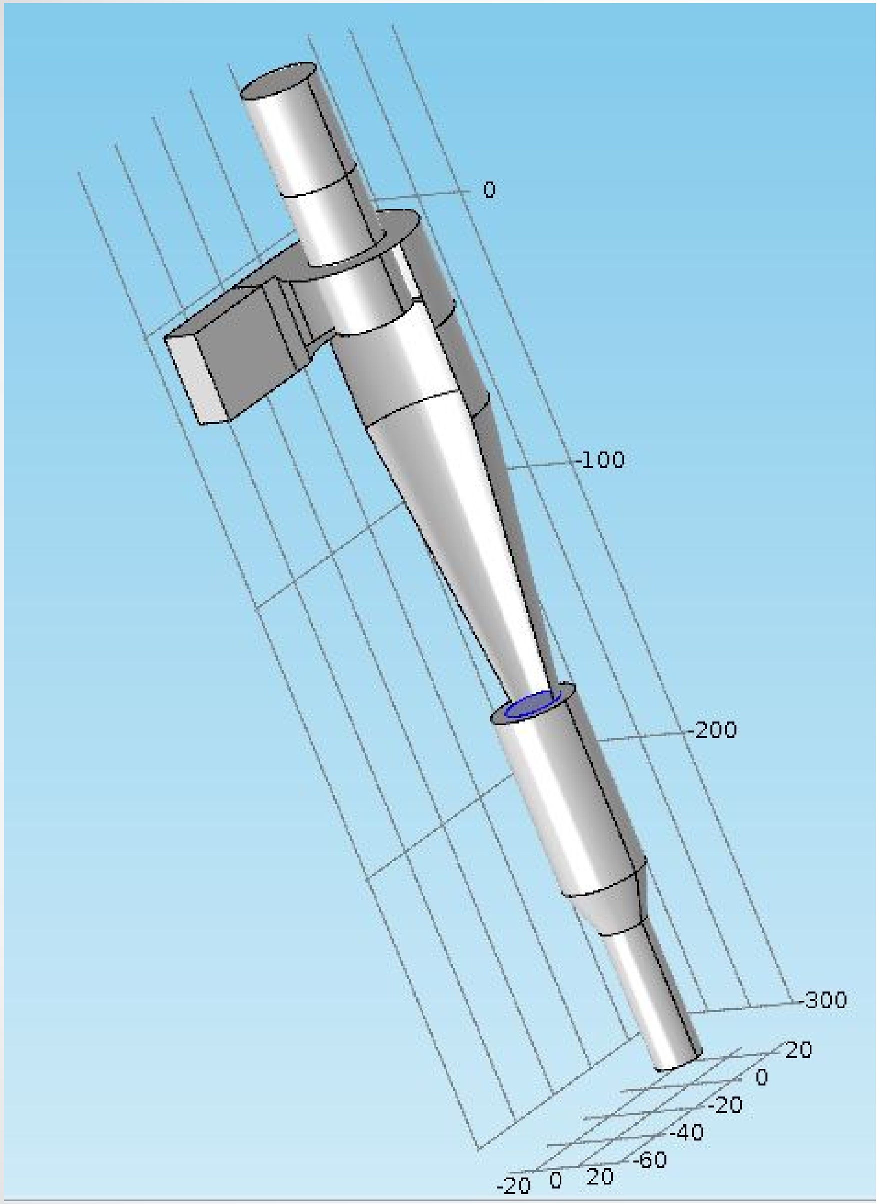
high efficiency cyclone

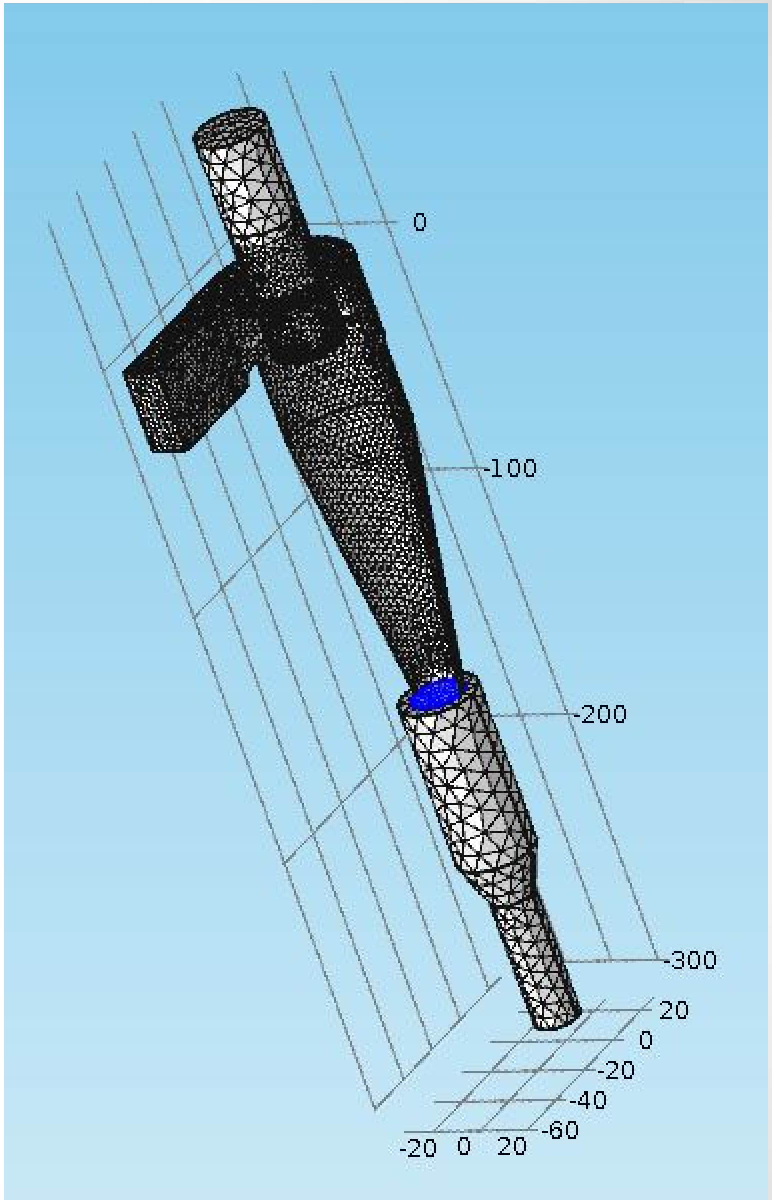
Cyclone Sizing and Dimensions

Description	Variable	Model Input	Cyclone 1 (inches)	Cyclone 2 (inches)	Cyclone 3 (inches)
Barrel Diameter	D	D	50	50	66
Barrel Height	M	M/D	1.3	1.3	1.3
Cone Height	L	L/D	2.07	2.07	2.07
Hopper Height	N	N/D	1.63	1.63	1.63
Cone Diameter	T	T/D	0.4	0.4	0.4
Vortex Finder Diameter	F	F/D	0.535	0.35	0.356
Inlet Width	A	A/D	0.285	0.285	0.216
Inlet Height	B	B/D	0.64	0.64	0.4848



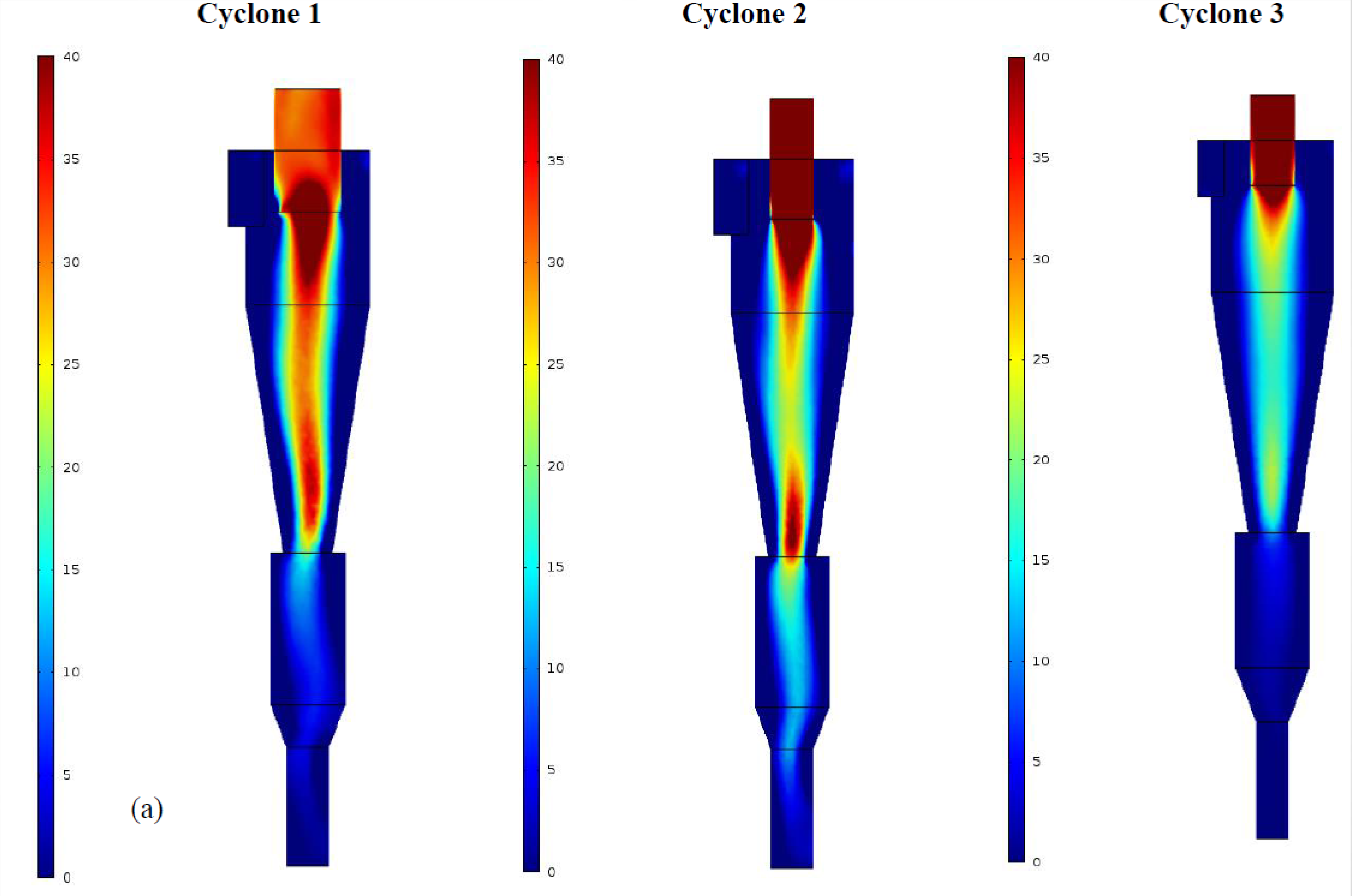



0
-100
-200
-300
20
0
-20
-40
-60
-20
0
20

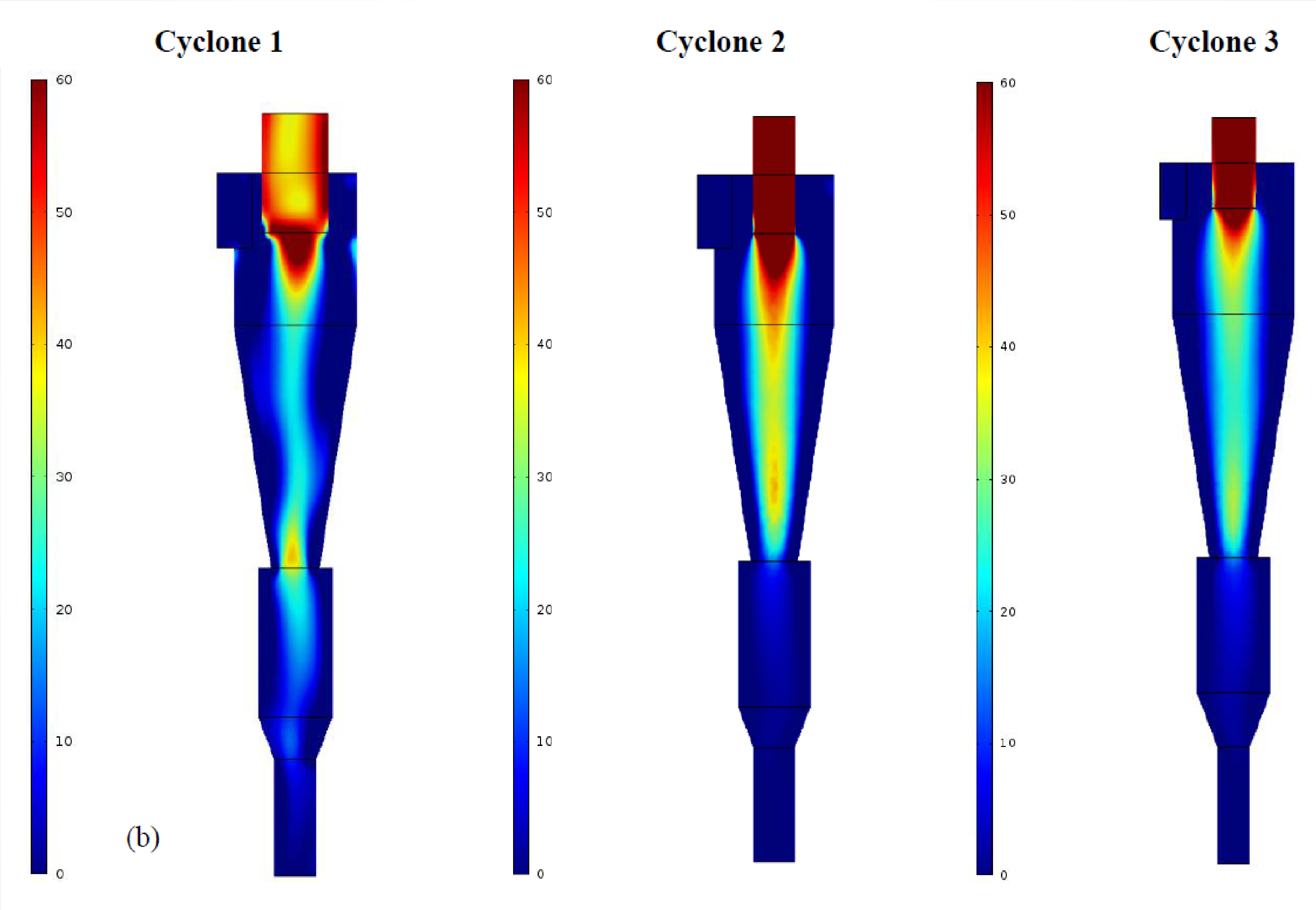

0
-100
-200
-300
20
0
-20
-40
-60
-20
0
20

Vortex Structure

- Can provide useful information regarding erosion and collection efficiency.
- There is not an exact apex or termination point of the vortex.
  - Subjective to how the profile is portrayed
  - Vortex can dissipate after entry into the hopper
- Following the gas path can give clues about the particle path.
- Vortex length is related to erosion in the hopper and dipleg.

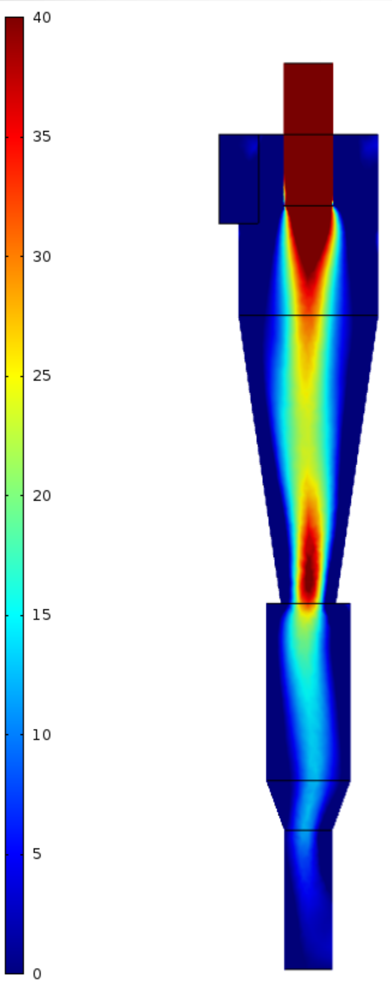


Axial velocity at (a) **40** fps inlet

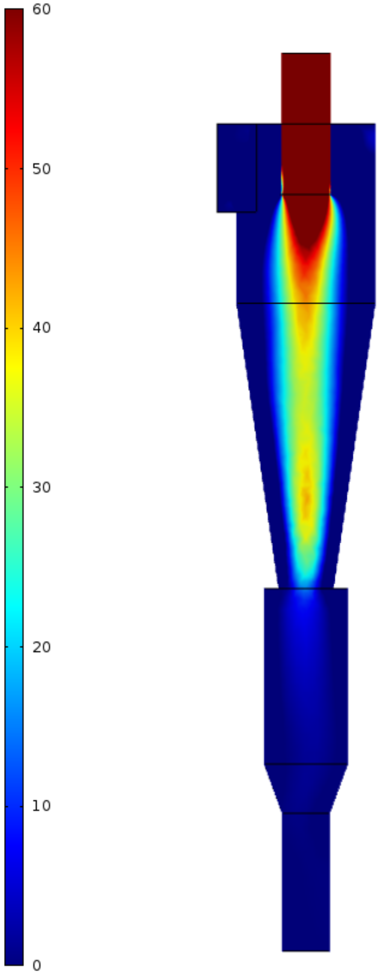


Axial velocity at (b) **60** fps inlet.

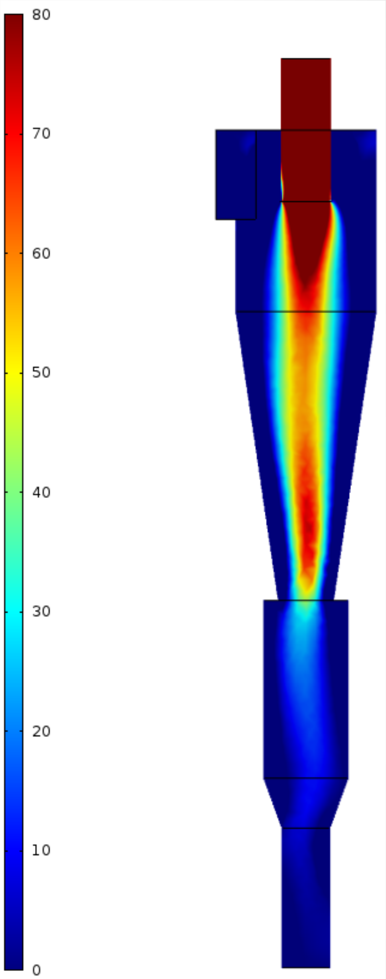
Cyclone 2: Axial Velocity



40fps



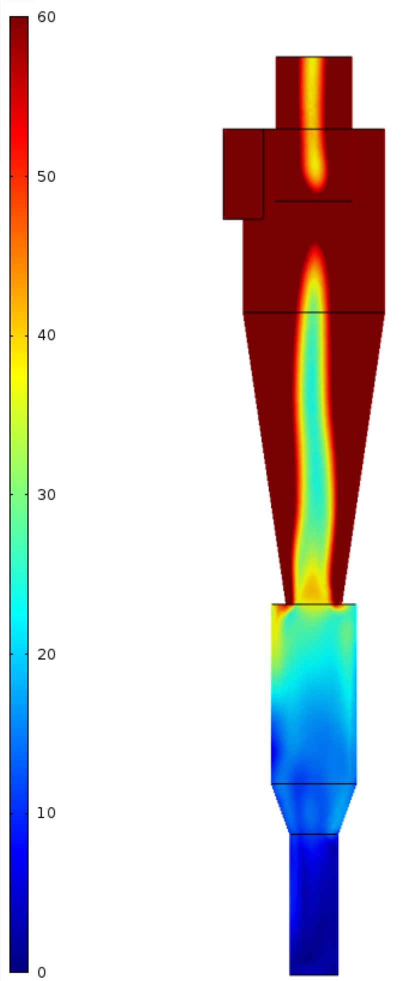
60fps



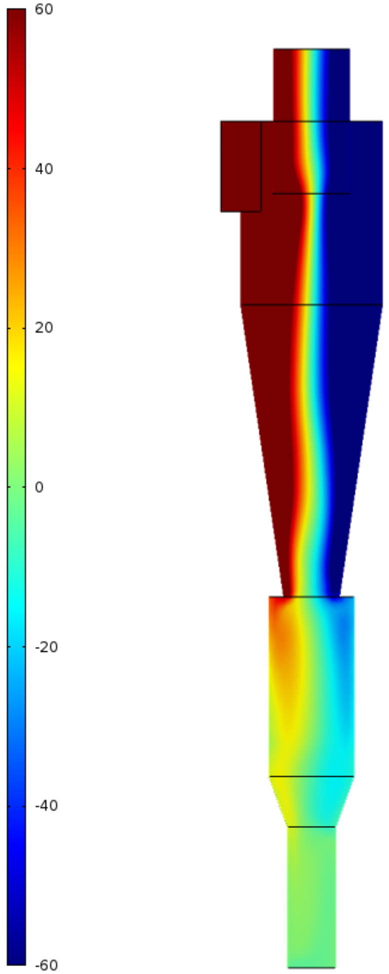
80fps

Velocity: Cyclone 1

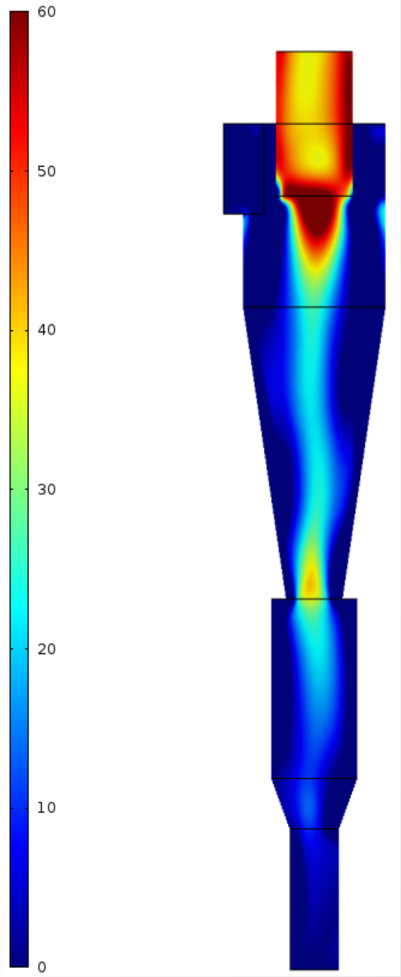
60fps Inlet



Velocity Magnitude

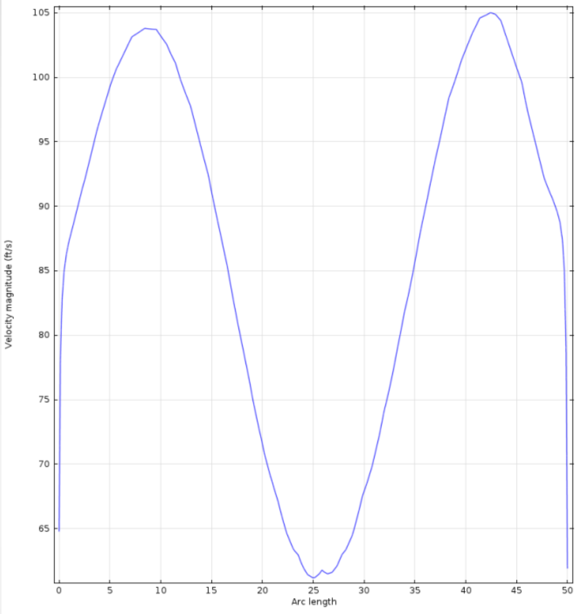


Tangential Velocity

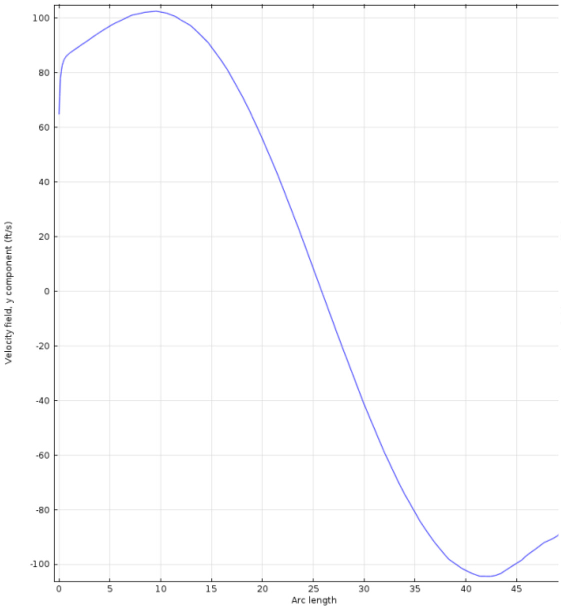


Axial Velocity

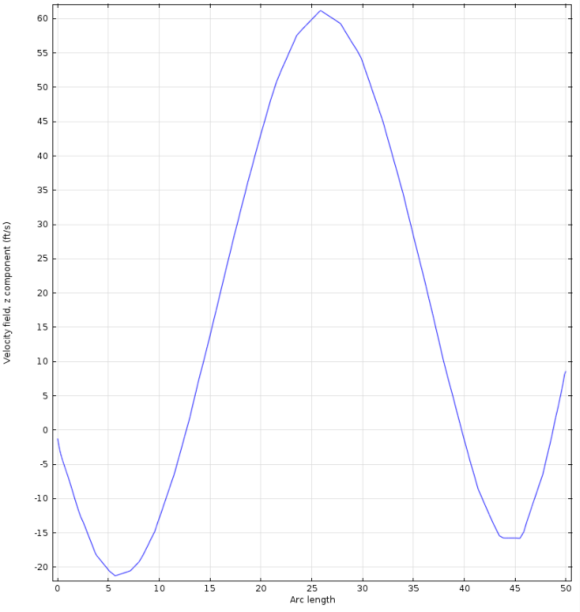
Cyclone 1 at 40inches below cyclone roof, 60fps inlet velocity



Velocity magnitude

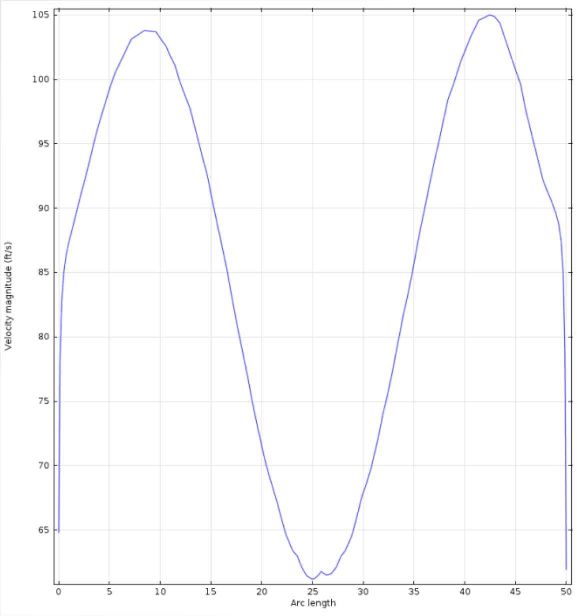


– Tangential velocity

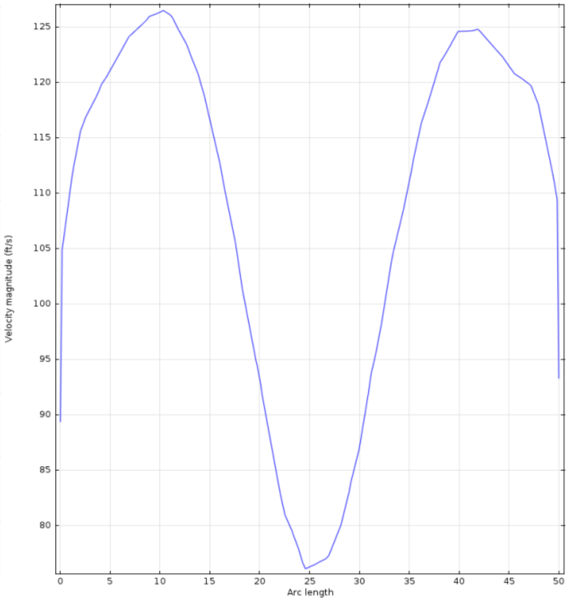


– Axial velocity

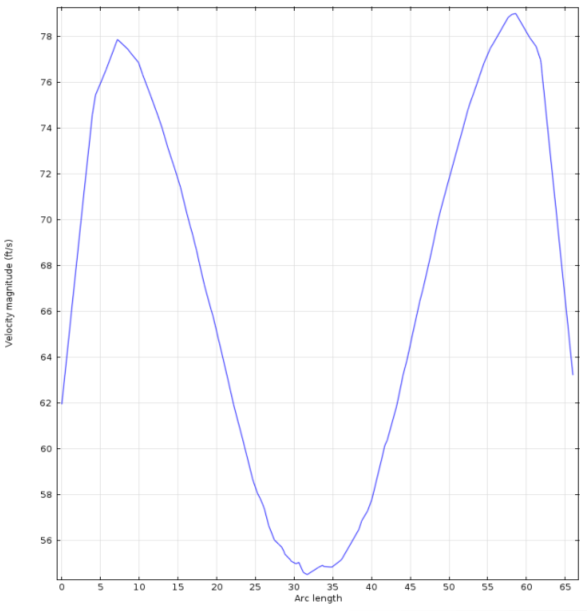
Cyclone 1



Cyclone 2



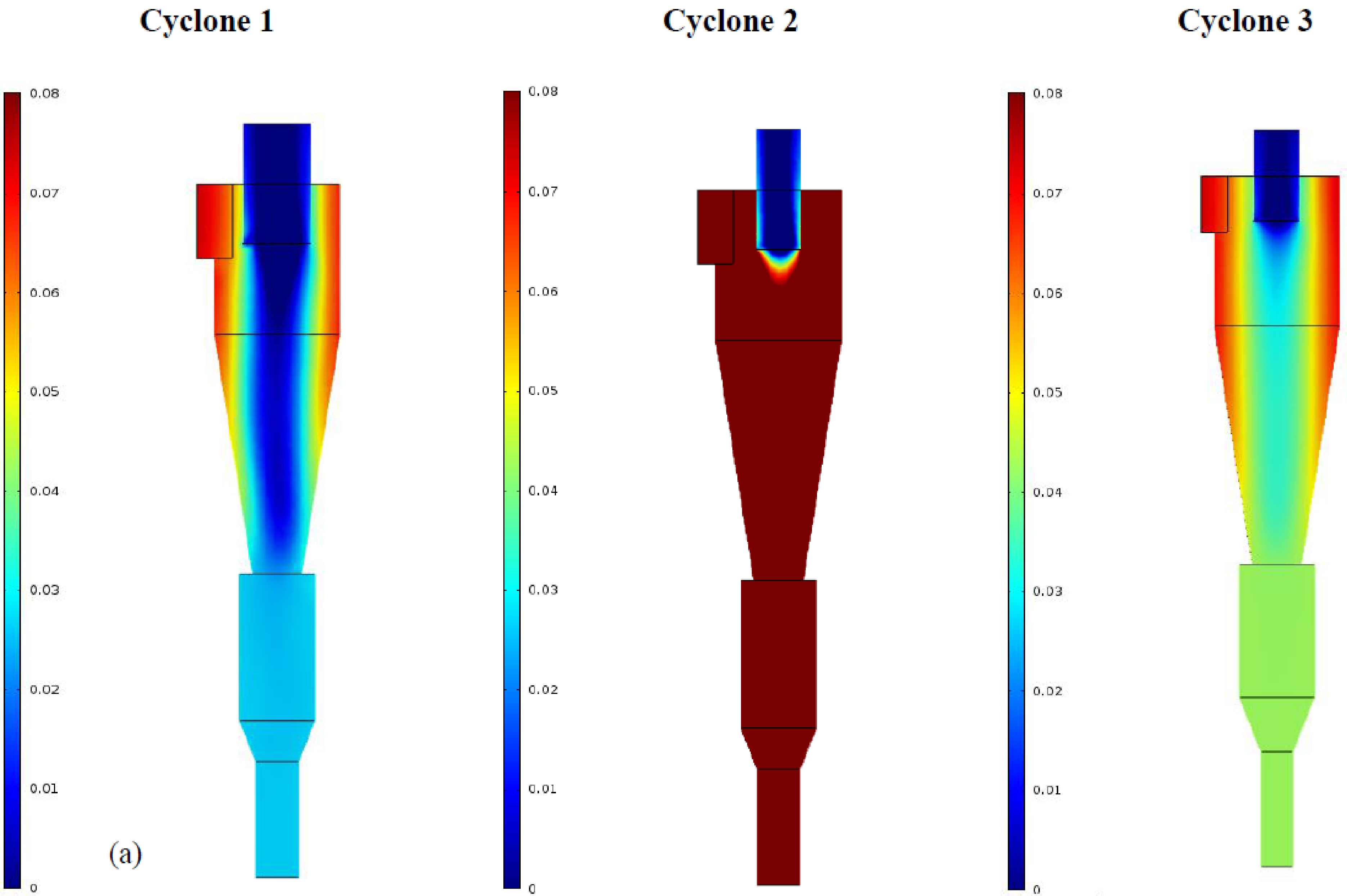
Cyclone 2



Velocity magnitude at 40inches below cyclone roof, 60fps inlet velocity

Pressure Loss

- Pressure loss of a cyclone is often inversely related to cyclone efficiency.
- Increasing the inlet velocity of a cyclone will often increase the efficiency, but at the cost of increasing the pressure loss.
- It has been determined that approximately 80% of the pressure loss is due to the viscous stresses.
- The remaining loss of pressure occurs at the inlet and outlet of the cyclone and by frictional forces along the cyclone wall.

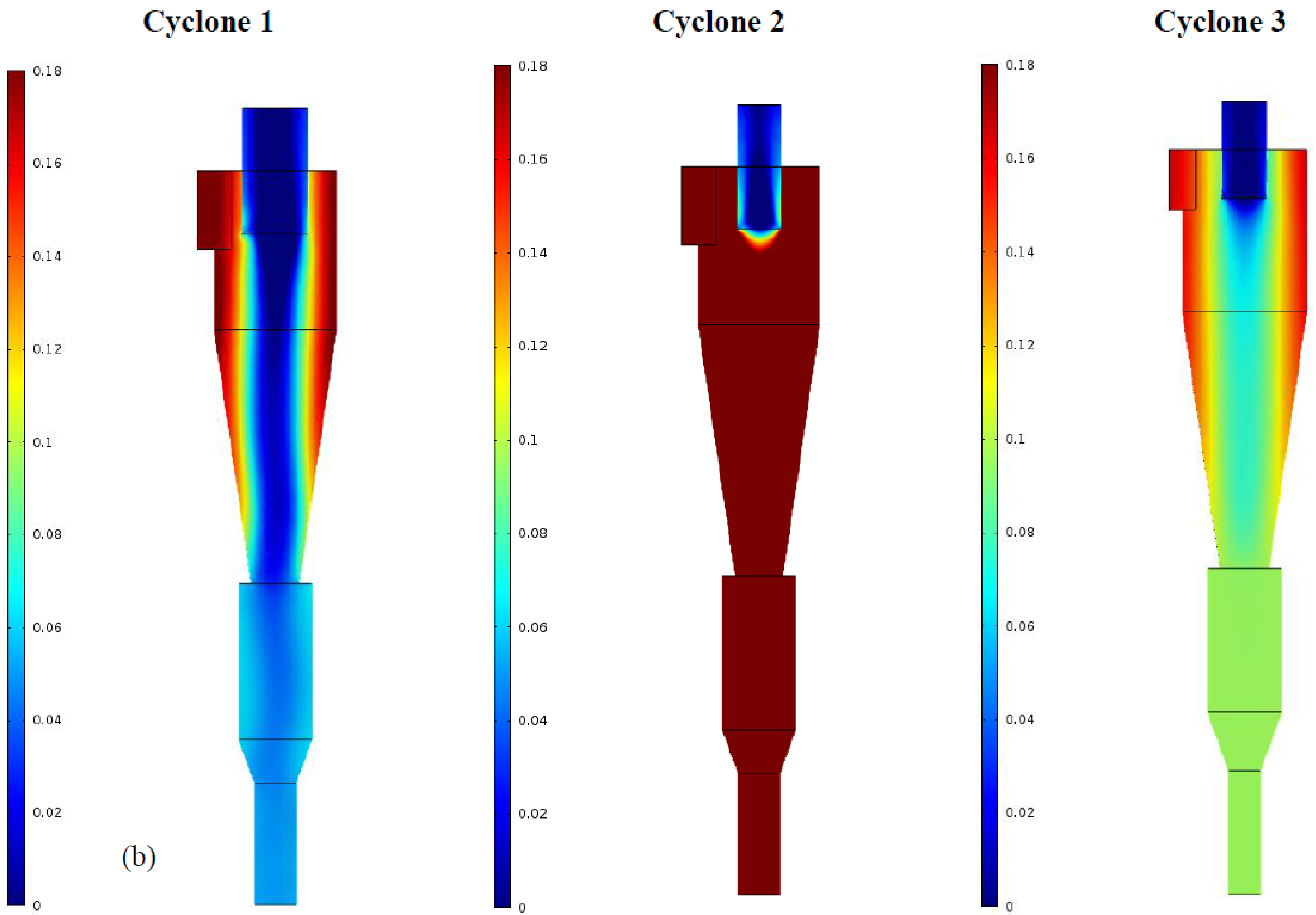


Cyclone 1

Cyclone 2

Cyclone 3

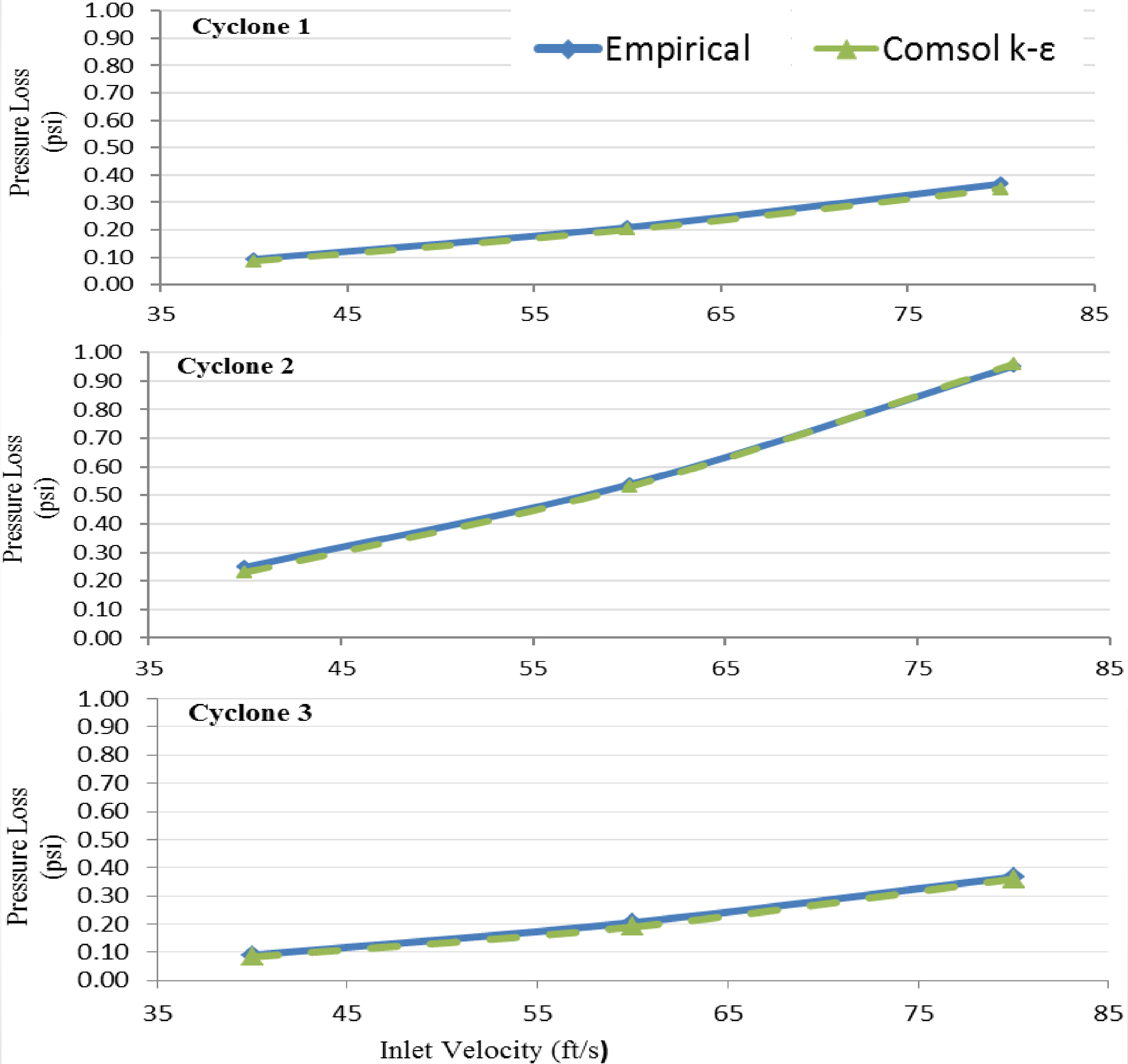
Static pressure at (a) **40** fps


Cyclone 1

Cyclone 2

Cyclone 3

Static pressure at (b) **60** fps


Cyclone 1
Empirical
Comsol k-ε
Pressure Loss (psi)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
35
45
55
65
75
85
Cyclone 2
Pressure Loss (psi)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
35
45
55
65
75
85
Cyclone 3
Pressure Loss (psi)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
35
45
55
65
75
85
Inlet Velocity (ft/s)

Pressure Loss

Cyclones 1 and 3 show high pressure regions along the walls. This implies that pressure loss due to drag is dominant.

Cyclone 2 has a modified outlet tube – meaning the outlet area is much less than the inlet area. This increases the outlet velocity.

COMSOL produces pressure loss with an average percent error of about 3% with the error decreasing with increasing inlet velocity.

Conclusions

- The simple geometry of cyclones is deceptive.
  - Turbulent flow is highly complex.
  - Small changes in geometry can produce major effects on performance.
- Cyclones are highly efficient making efficiency increases difficult to detect.
- Model is lacking the effects of anistropic turbulence

Conclusions

- Cyclones push the limits of CFD code and solvers.
  - Anisotropic turbulence requires very robust and computationally costly solvers.
  - Need to model particle influence on the gas stream

- All parameters of cyclone performance must be considered during design.