Computational Fluid Dynamics Model of a Cyclone Separator

Brad Frye
Dr. Kevin Crosby
Carthage College

Abstract

Air cyclones are a promising technology for first stage air filtration in future lunar habitats where lunar dust mitigation is a mission critical concern. Our experimental work with cyclones in microgravity as part of NASA's Systems Engineering Educational Discovery (SEED) program suggested that gravity does not play a significant role in the operation of the air cyclone. If correct, this result paves the way for further study of cyclone filtration in microgravity.

Building on the SEED research, in this project we develop a computational fluid dynamics (CFD) model of the cyclone used in the experimental work in reduced gravity to address the following questions:

- How does collection efficiency scale with gravity?
- What are the dynamical forces acting on particles in an air cyclone?
- Can we understand our results in terms of these dynamical forces?

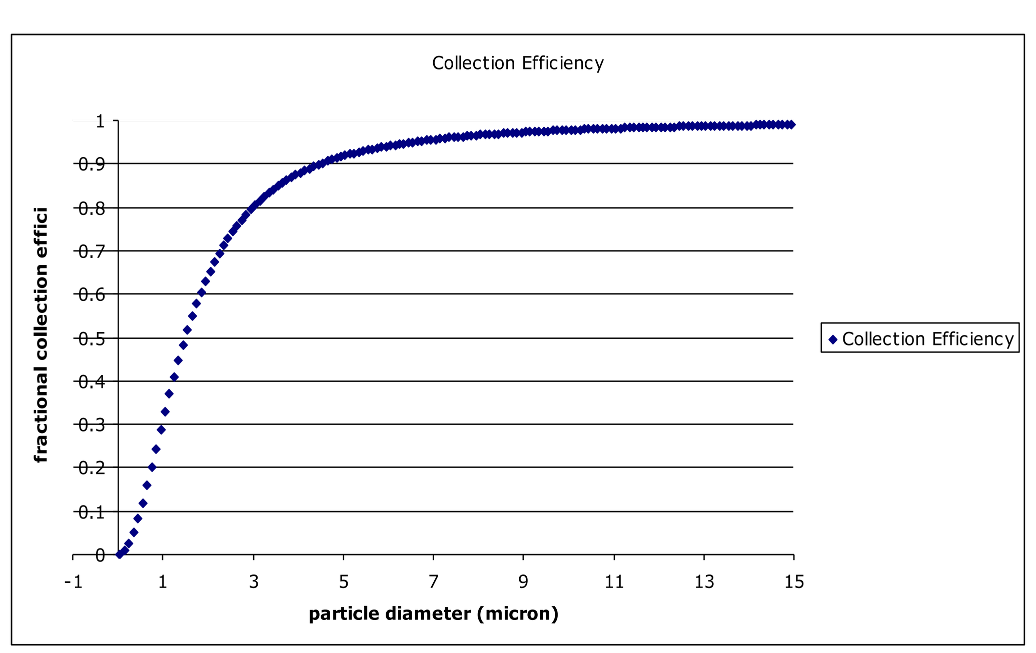
Empirical Model

The collection efficiency varies as a function of particle size. We can use an empirical model (Lapple Model) to estimate the particle diameter d_{50} at which 50% of the dust particles should be collected. The parameters determine the empirical efficiency estimate e_i for particles of diameter d_i.

$$d_{50} = \left[\frac{18\mu W^2}{2\pi(2L_{cylinder} + L_{cone})V_i(\rho_p - \rho_g)}\right]^{1/2}$$

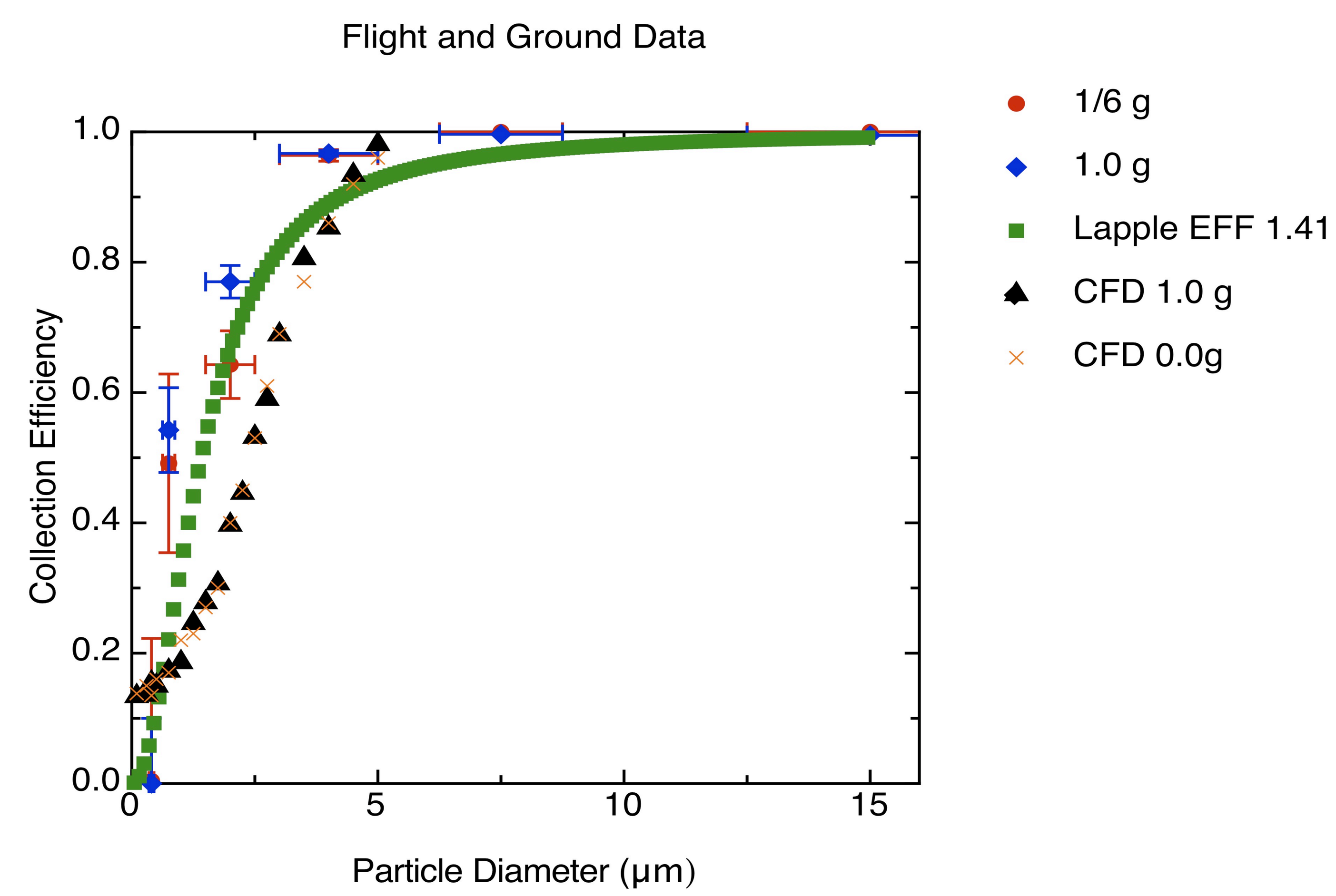
$$e_i = \frac{1}{1 + (d_{50}/d_i)^2}$$

Here, $V_i = 10$ *m/s* is the inlet velocity, $\mu = 1.75\times10^{-5}$ *kg m/s* is the kinematic viscosity of air, $\rho_p = 2900$ *kg/m³* is the density of the particle, $\rho_g = 1.30$ *kg/m³* is the density of air, $W = 0.025$ *m* is the cyclone's inlet diameter, $L_{cylinder} = 0.105$ *m* is the length of the cylindrical region, and $L_{cone} = 0.140$ *m* is the length of the conic region.



Collection efficiency increases with particle diameter. We expect d_{50} = 1.4 microns for our cyclone.

CFD Results: Collection Efficiency



Analysis

Our CFD data validates our experimental finding that gravity does not significantly affect collection efficiency. To better understand this result, we have developed a mathematical model of particle capture in a cyclone.

Radial and tangential motions of particles of diameter d_p are coupled:

$$\dot{\theta}^2 = \frac{18\mu}{(\rho_p - \rho_g)d_p^2}\frac{\dot{r}}{r} \qquad (1)$$

Axial motion is independent of tangential and radial motion. Particles reach a terminal speed:

$$v_{zT} \equiv \dot{z}|_{\text{terminal}} = -\frac{(\rho_p - \rho_g)d_p^2}{18\eta}g \qquad (2)$$

which is on the order of 10^{-4} m/s for 1 micron particles.

For simplicity, we assume a rigid body-type circulation:

$$\omega \equiv \dot{\theta} = v/r \qquad (3)$$

where *v* is the tangential speed of the flow. Integrating Eqn. (1) under the assumption of Eqn. (3), we determine the *residence time* of a particle as it swirls from an inner radius R_0 to collection at radius R:

$$\tau_{residence} = \frac{18\mu}{\omega^2 d_p^2(\rho_p - \rho_g)}\log\left(\frac{R}{R_0}\right)$$

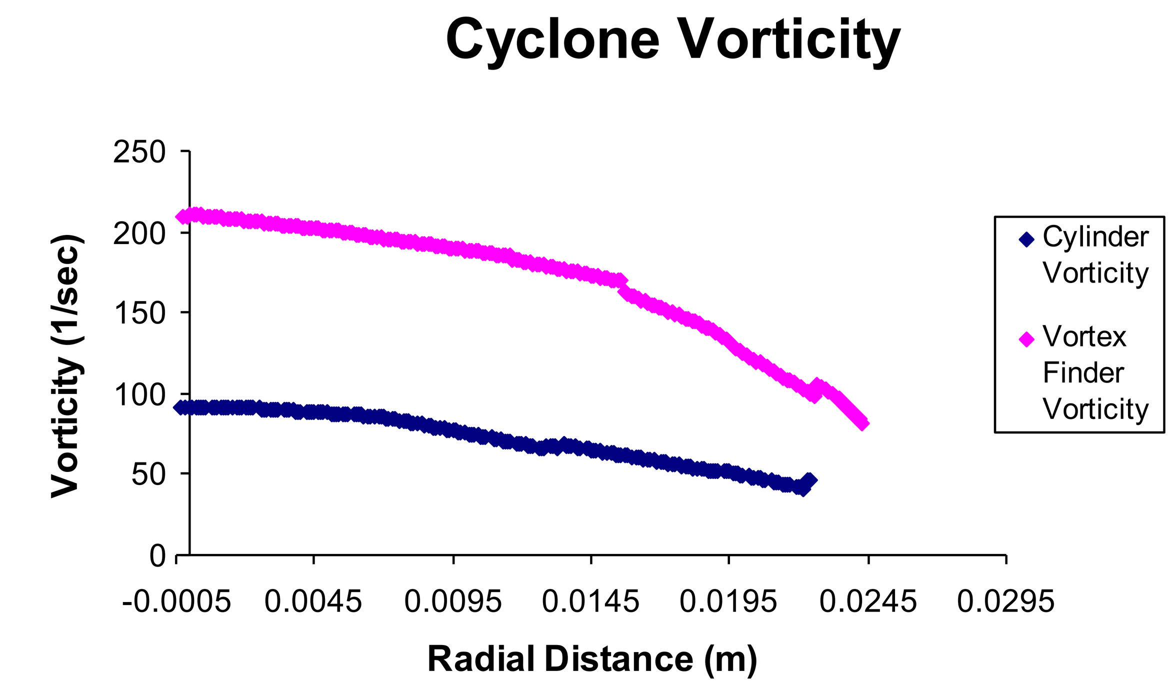
A particle is assumed collected if its residence time is less than the residence time of air; therefore a particle with a low residence time has a better probability of being captured.

Important Result:
Independent of gravity!

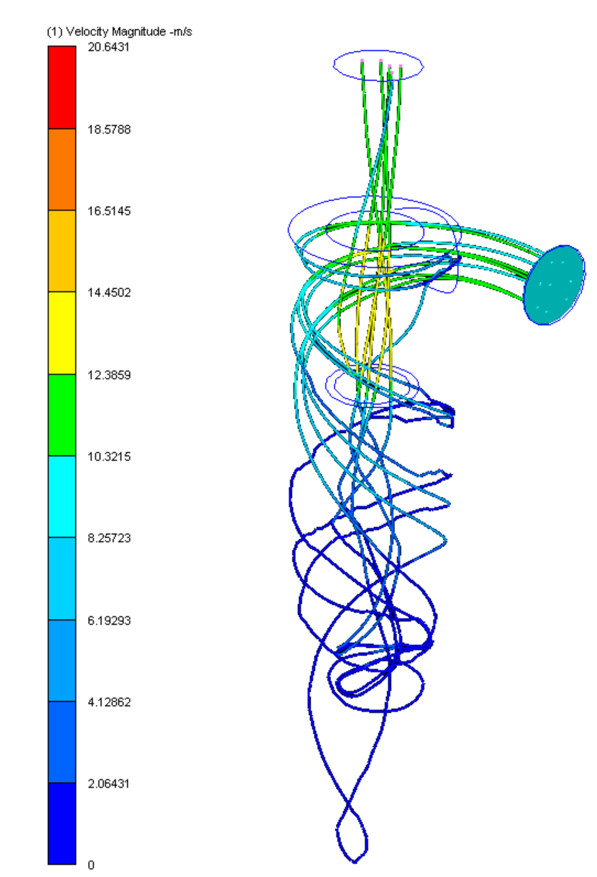
$$\tau_{residence} \propto d_p^{-2}$$

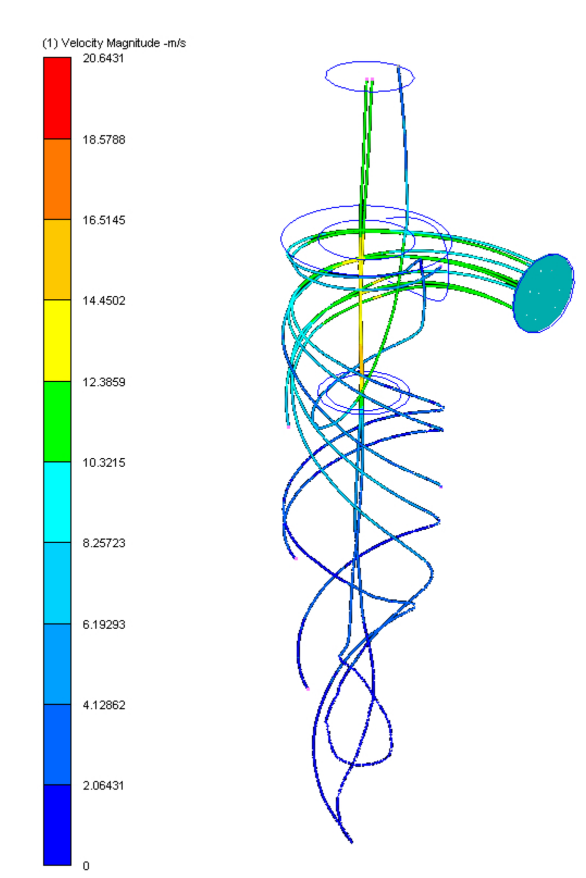
CFD Results: Vorticity

Vorticity $\Omega = \nabla \times \mathbf{v}$ is a measure of the "swirl" of the flow. If the flow field is well approximated by the rigid body motion we assumed in our analysis, we'd expect $\Omega = 2\omega$. Our numerical results for the scalar vorticity suggest that rigid body motion is strictly only present in the inner core of the swirl field.

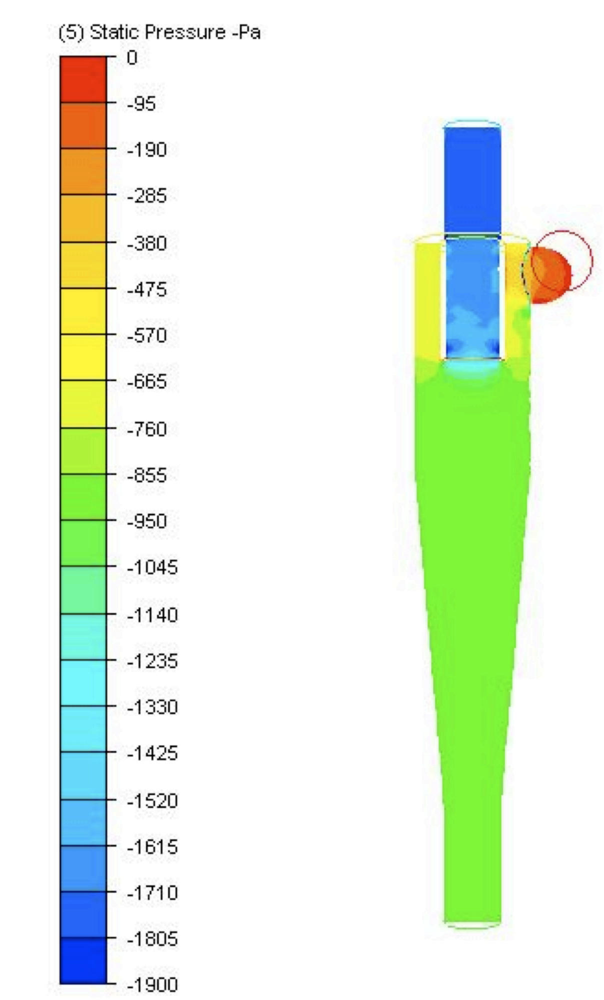


CFD Results: Flow Dynamics





We used particle traces to observe the air flow and particle behavior in the cyclone. Shown above are massless air traces (top), in which all traces escape to the outlet; and 0.5 micron massed traces (bottom), in which some particles escape, and the others are trapped on the cyclone wall.



Our simulations reproduce the experimentally observed pressure drop across the cyclone. Increased pressure drop is the trade-off for increased collection efficiency. The static pressure drop across the cyclone is approximately 900 Pa in good agreement with our experimental results.

Summary

Residence time is directly proportional to $d_{particle}^{-2}$. The absence of a gravity term shows that gravity has a negligible effect on residence time; it only affects a particle's vertical position at a given time. Therefore, gravity should have little effect on the cyclone's collection efficiency. Our experimental and numerical work confirm this result.