Numerical Investigation of Synthetic, Buoyancy-Induced Columnar Vortices

Nicholas Malaya

Department of Mechanical Engineering
The University of Texas at Austin

April 18th, 2016

Acknowledgment: This material is based upon work supported by the Department of Energy [ARPA-E] under Award Number [DE-FOA-0000670]

The dust devil phenomenon

Turbulent, unstable motions

- Incident solar energy absorbed into ground
- Ground heats air by conduction
- Heated air expands, lowering density, driven upward by force of buoyancy
- Arizona in Summer ($\Delta T = 30$ K)
- $Ra \approx 10^9 - 10^{11} \rightarrow$ unstably stratified fluid
- Velocities can exceed 33 m/s.

How much energy is present in one of these objects?

Energy Estimate [Sinclair]

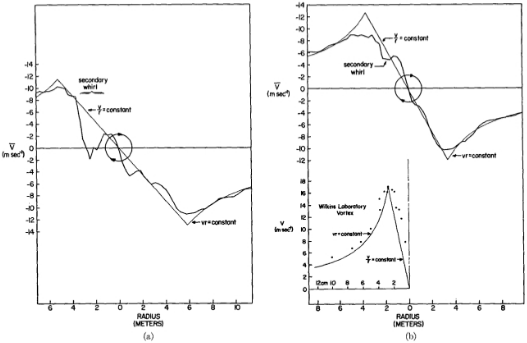
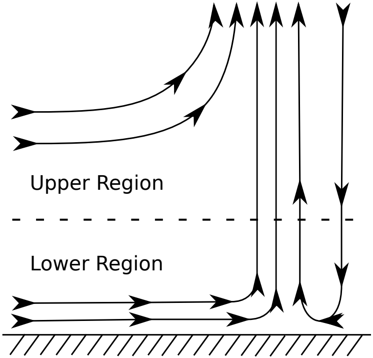


FIG. 11. Radial distribution of the mean tangential velocity at two levels, $z=7$ ft (a) and $z=31$ ft (b), for D-D #1 with superimposed Rankine combined profiles.

- Estimate energy by integrating Sinclair profile
- R $\approx$ 6 meters, $V_\theta \approx 11$ m/s, $V_z \approx 10$ m/s
- Energy flux through horizontal plane $= \frac{1}{2}\rho \int V_z(V_z^2 + V_\theta^2)\, dA$
- $P \approx 24$ kW

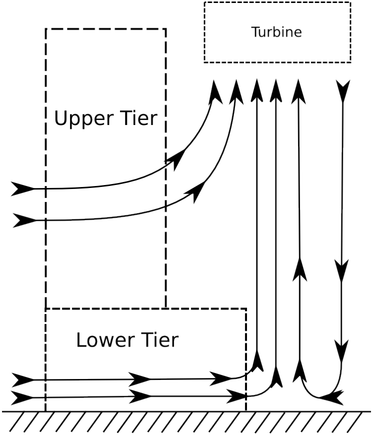
Dust Devil Structure [Sinclair,Kanak,Renno]



Dust devil structure

- Driven by buoyancy of hot ground
- Near surface: radial inflow spinning region (core)
- Downward flow in hot, low-pressure center ("eye")
- Fluid from higher region entrained (inviscid potential flow region)
- Characterized by strong rotation
  - What generates vorticity?
    - vortex stretching
    - vortex tilting

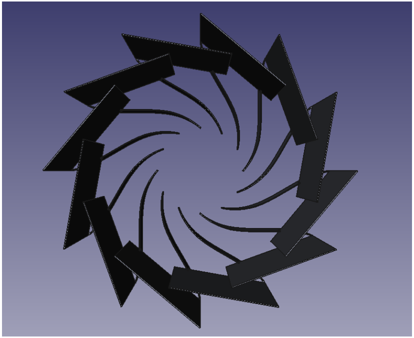
Synthetic Dust Devils

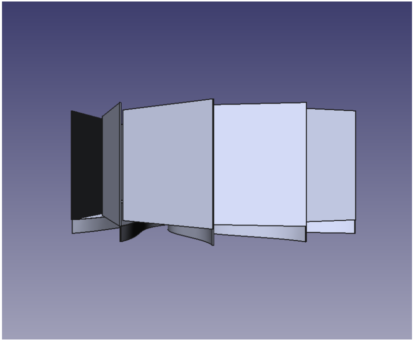


Motivation

- Engineer synthetic vortices for energy generation
  - Two tier configuration mimics natural phenomenon
  - Turbine at upper tier vanes to extract energy
- Difficult to explore space experimentally
  - Field tests in Arizona (GT)
  - expensive to alter configuration
  - difficult to measure everything

Example configuration





Turning Vanes

- Several (typically 12) control surfaces used to turn the flow
- Top tier significantly taller than the bottom
- A cone may be added to the top to contract the flow

Modeling Objectives

System Configuration

- Probe and optimize configuration with CFD
  - Vanes
  - Cone (and solid surfaces)
  - Turbine
- Inform design for 2016 field test
  - Predict energy output
  - Sensitivities to design
  - Sensititivies to conditions

Scenario Space

- Atmospheric model
- Impact of buoyancy
- Effect of wind

Dynamical Equations

The equations describing fluid flow with natural convection are,

$$\frac{\partial u}{\partial t} + u \cdot \nabla u = -\frac{1}{\rho}\nabla P + \nu \nabla^2 u - g\frac{T - T_0}{T_0} \quad (1)$$

$$\nabla \cdot u = 0 \quad (2)$$

$$\rho c_p \frac{\partial T}{\partial t} + u \cdot \nabla T = \nabla \cdot (K \nabla T) \quad (3)$$

- Incompressible N-S + Boussinesq buoyancy
- Temperature variation small compared to mean temperature
- Low mach number

However, $Ra \approx 10^9 - 10^{11}$ – Need turbulence model!

Atmospheric Viscosity Model

Introduction to Monin-Obukhov

- Under stationary, homogeneous conditions turbulent quantity $\bar{f}$,

$$\bar{f} = f(z, \frac{g}{T_0}, \rho_0, U_\infty, q, \nu_l, K_l) \tag{4}$$

- 5 parameters - 4 dimensions = 1 dimension-less group:

$$\xi = -\frac{\kappa \frac{g}{T_0} \frac{q}{c_p \rho_0} z}{U_\infty^3} \tag{5}$$

- Interpret as a length scale,

$$\xi = \frac{z}{L_{M-O}}; \quad L_{M-O} = -\frac{{U_\infty}^3}{\kappa \frac{g}{T_0} \frac{q}{c_p \rho_0}} \tag{6}$$

- L_{M-O} is height where shear production $\approx$ buoyancy

Atmospheric Viscosity Model

M-O, cont.

By similarity, mean turbulent quantities are functions of the non-dimensional group,

$$\frac{\bar{f}}{f_{MO}} = \phi(\frac{z}{L_{M-O}}) \tag{7}$$

e.g.

$$\bar{u}(z) = \frac{U_\infty}{\kappa}\phi_u(\frac{z}{L_{M-O}}) \quad \text{and} \quad \frac{\partial \bar{u}(z)}{\partial z} = \frac{U_\infty}{\kappa L_{M-O}}\varphi_u(\frac{z}{L_{M-O}}) \tag{8}$$

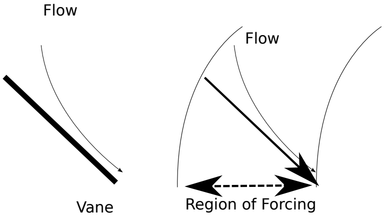
Our interest is in the eddy viscosity, $u'v' = \nu_T \frac{\partial \bar{u}}{\partial z}$ where $\xi \to -\infty$,

$$\nu_T = \frac{1}{C_{\nu_T}}\left(\frac{q}{c_p \rho_0}\frac{g}{T_0}\right)^{\frac{1}{3}} z^{\frac{4}{3}} \text{ for } z \gg L_{M-O}. \tag{9}$$

Turning Vane Representation

Virtual Vanes

- Requirements:
  - Very general formulation
  - No re-meshing
- Volumetric forcing:
  - Vane surface not represented
  - Similar to actuator-disk



Formulation

- Unit normal to vane surface,

$$\mathbf{n}(\mathbf{x}) = \sin\left(\phi(r)\right)\hat{\mathbf{r}} + \cos\left(\phi(r)\right)\hat{\theta} \tag{10}$$

- Apply $\mathbf{f_v}$ to force flow parallel to vanes,

$$\mathbf{f}_v = -\frac{1}{\ell_v}|\mathbf{u}|(\mathbf{u}\cdot\mathbf{n})\mathbf{n} \tag{11}$$

Numerics

Formulation

- Using Galerkin FEM discretization (N-S in weak form)
- Stabilized with SUPG stabilization *al la* Hughes/Becker+Braack
  - Adjoint stabilization scheme (τ)
  - Circumvents Babuska-Brezzi (we are using linear elements)
- Time discretization via backward Euler (if not steady)
- Newton method used to solve resulting non-linear implicit system

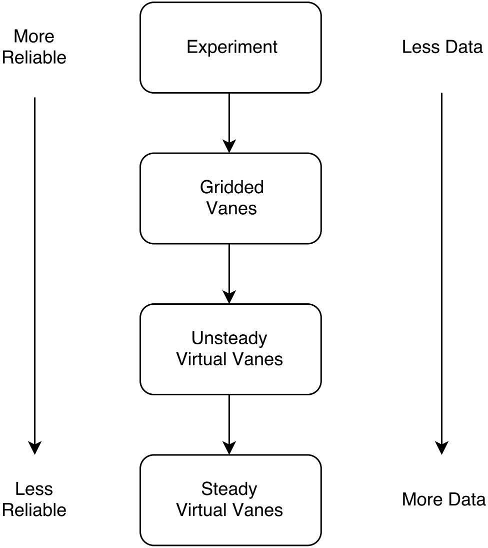
Software

- Using GRINS(+Libmesh) library developed by Bauman and Stogner

Hardware

- Most of the runs performed on LS4,LS5, Stampede at TACC
- 264-528 processing cores
- Several million degrees of freedom for each run, locally $O(10^4)$

Modeling Hierarchy



Steady vs. Transient Virtual Vanes

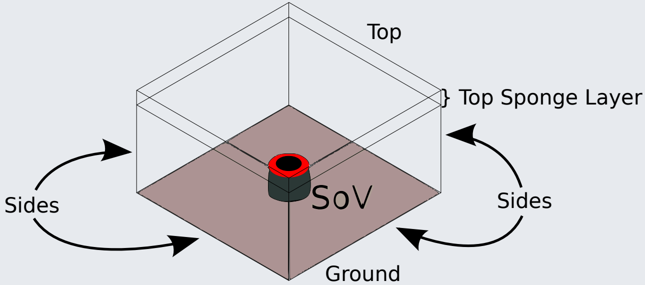
Unsteady VV

- Transient, like V-LES
  - captures dynamics of plume and wake
- Solutions temporally averaged
- Run-time ≈ 12 hours

Steady VV

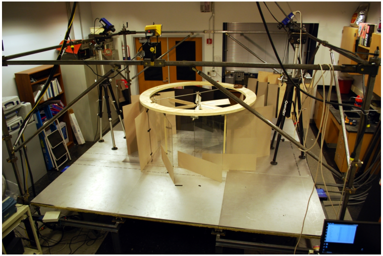
- Steady, like RANS (no $\frac{\partial()}{\partial t}$)
  - no dynamics
- Run-time ≈ 2 minutes
- Critical design tool

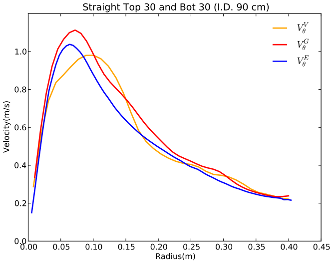
No Wind (Thermal-Only)



- Domain extents scaled by system diameter
- Sides are periodic
- Sponge layers are finite thickness high viscosity boundaries
- Top has special mixed B.C.

Tabletop Experiment Validation





Laboratory Comparison of Azimuthal Velocity

- Slightly different B.C.s (inflow)
- Straight, single-tier, thirty degree vanes
- Red: Gridded, Blue: Experiment, Gold: Virtual
- Gridded consistent with experimental data
- Virtual vane solution more diffuse, incorrect peak predict

Thermal-Only Virtual Vanes

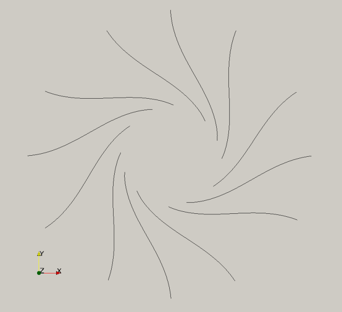


Figure: Bottom Vanes

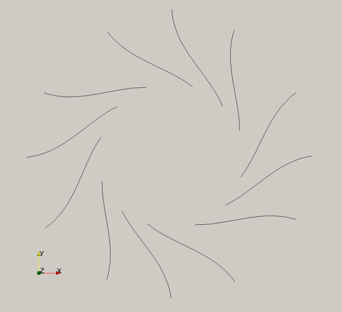


Figure: Top Vanes

Two Tier Configuration

- Curves drawn by advancing particle through forcing field
- No cone
- The top and bottom tier final angles are 70° and 85°, respectively

Probing the Solution: Vertical Slices

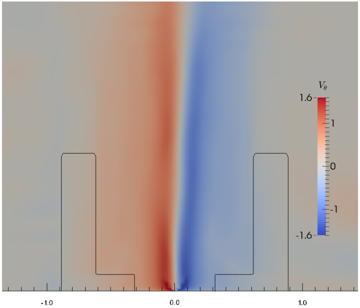


Figure: Azimuthal velocity

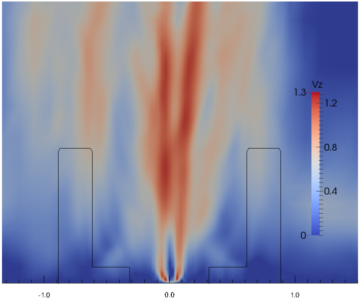
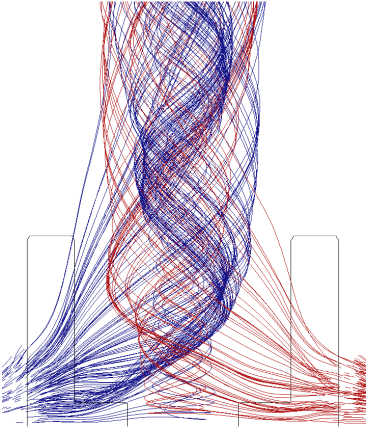


Figure: Vertical velocity

Velocity Observations

- Slices are temporally averaged virtual vane cases
- Virtual vane forcing region outlined in black
- Velocity highest in tight region near center

Solution structure



Particle Paths

- “Seed” particles outside of device
- RK4 to advance the particles through the velocity field

Probing the Solution: Vertical Slices

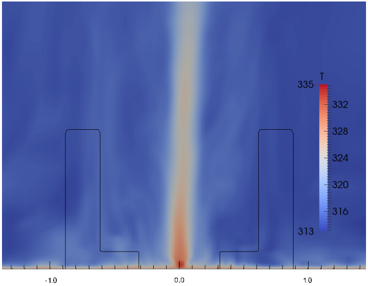


Figure: Temperature

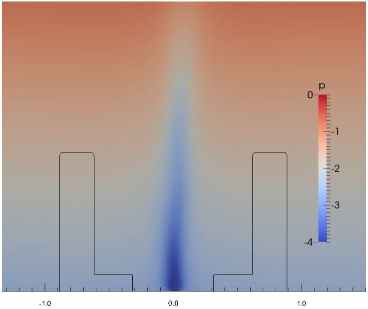


Figure: Pressure

Pressure and Temperature Observations

- Tight velocity core contains hot, low pressure “eye”

Probing the Solution: Horizontal Slices

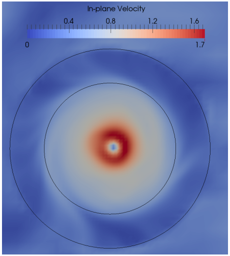


Figure: In-plane Velocity

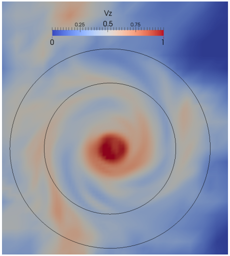


Figure: Vertical Velocity

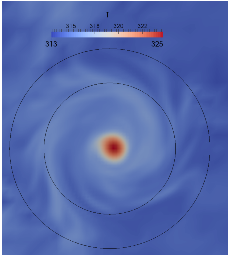
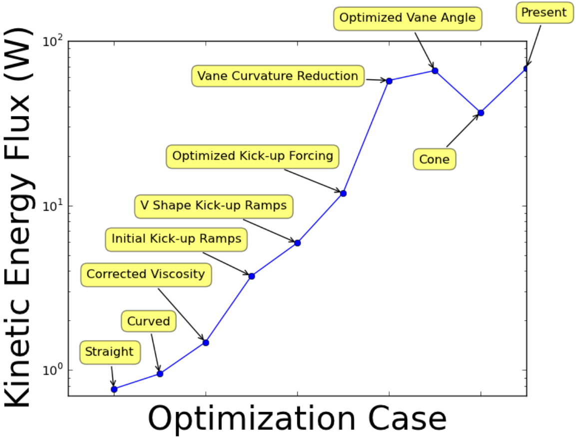


Figure: Temperature

Observations

- Slice taken at the height of the 2nd tier of vanes

Optimizing the Thermal-Only Configuration

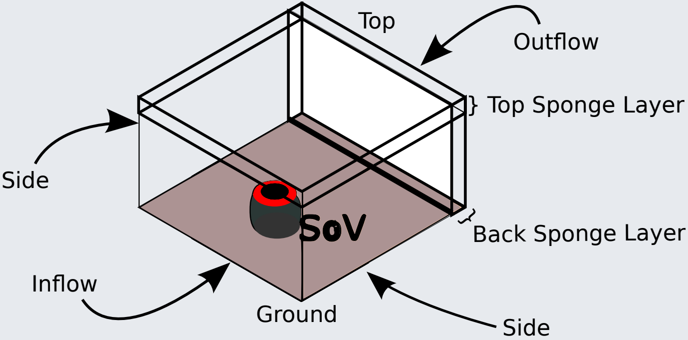


Kinetic energy flux,

$$\dot{E} = -\frac{\rho}{2}\int V_z(V_\theta^2 + V_z^2)dA$$

- 78X increase in flux!
- Performed by exploration of design space
- flux < 100 Watts

Wind Cases



- Specified Inflow (Dirichlet)
- Top and Outflow have special mixed B.C.
- Sponge layers on Top and Outflow
- Natural (do nothing) boundaries on the side (Neumann)

Simulation Geometry and Boundary Conditions, cont.

Specified Inflow

- 7th order turbulent boundary layer,

$$u_{\text{in}}(z) = U \text{ min } \left(\left(\frac{z}{\delta}\right)^7, 1 \right)$$

- The thermal inflow is then,

$$T_{\text{in}}(z) = \Delta T \left(1 - \text{ min } \left(\left(\frac{z}{\delta}\right)^7, 1 \right) \right) + T_0 {-2z/3}.$$

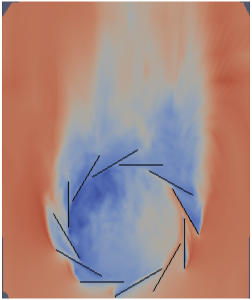
Ground

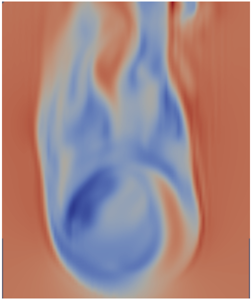
- modeled with a Dirichlet boundary condition such that,

$$\overrightarrow{u} = 0 \quad \text{on } \Gamma_G$$
$$T = T_g$$

Cold Wind Tunnel Validation

Streamwise Velocity

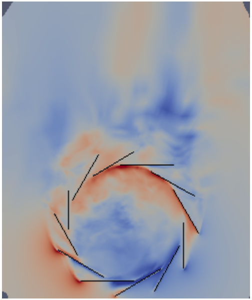


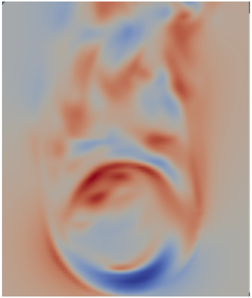


Horizontal slice (midway through the 60° vanes)

- Constant velocity wind, no temperature gradient
- Gridded vanes on left, Virtual vanes on right
- Flow penetrates vane region where aligned
- Results qualitatively agree with wind tunnel observations

Wind Tunnel: Spanwise Velocity





Horizontal slice (midway through the 60° vanes)

- Gridded Vanes on left, Virtual Vanes on right
- Not particularly accurate in the wake region
- Virtual vanes reproduce direction and magnitude of spanwise velocity
- Flow does not penetrate out back of device

Simulation of August Field Test

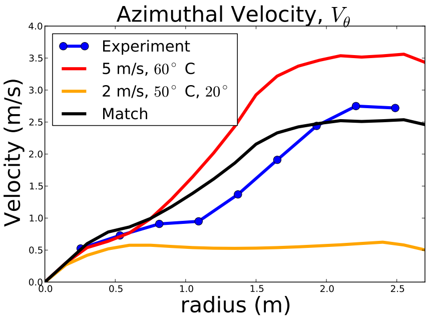
Model Problem

- Emulate field conditions in Arizona, August 2015
- Hot ground, ambient winds
- Lower tier, upper tier, and cone

Field Validation Study

Scenario parameter uncertainty

- Wind speed: 2-5 m/s
- Wind direction($\approx 20^\circ$)
- $T_s = 50 - 60^\circ$ C ($\approx 121 - 140^\circ$ F)
- No boundary layer temperature data (DAQ equipment malfunctioned)



- CFD broadly consistent with field observations
  - Experimental data extremely limited
- Kinetic energy fluxes match to within 10%

Wind Virtual Vanes

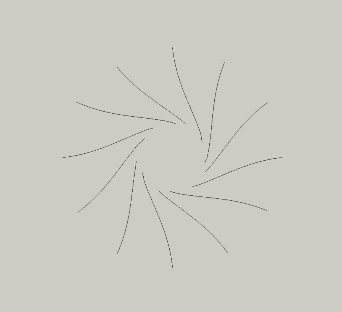


Figure: Bottom Vanes

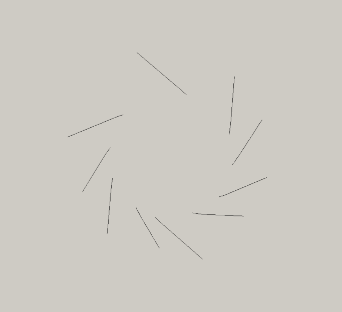


Figure: Top Vanes

Two Tier Configuration

- Curves drawn by advancing particle through forcing field
- Cone on top of 2nd tier of vanes
- The top and bottom tiers final angles are 70° and 80°, respectively

Horizontal images at height of the vanes

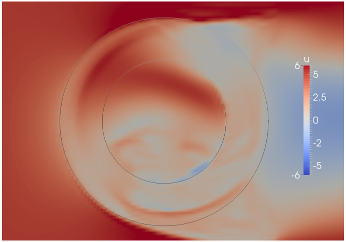


Figure: Streamwise Velocity

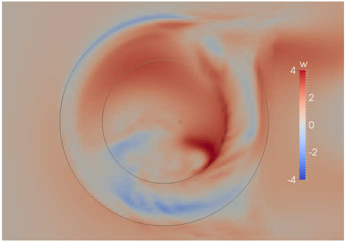
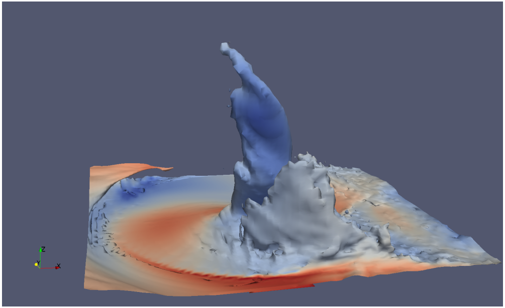


Figure: Vertical Velocity

Observations

- Freestream velocity is 5 m/s
- $\Delta T = 32$ K
- Some rotation visible in center

Temperature Plume



Temperature isocontour

- Potential temperature, $\tau(x, y, z) = T(x, y, z) - T_{\text{in}}(z)$
- Iso-contour corresponds to $\tau = 3K$ [Sinclair]
- Colored by streamwise velocity

Vertical Images

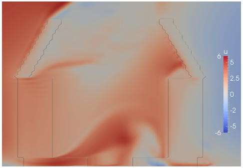


Figure: Streamwise Velocity

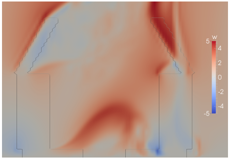


Figure: Vertical Velocity

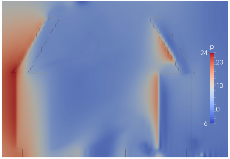


Figure: Pressure

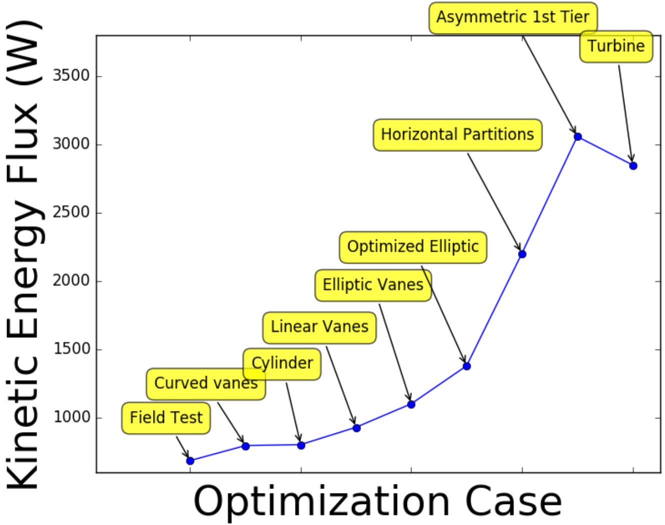
Observations

- 600 Watts of Kinetic Energy Flux
- Best achieved output from axisymmetric configurations

Timeline

April 2016	Conclude parameter sweeps and optimization of apparatus.
April 2016	Turbine actuator-disk verification, validation and prediction.
May 2016	Proposed configuration and predictions for experimental team.
July 2016	Comparisons between synthetic and natural dust devil physics.
Aug 2016	Validation against 2016 field data.
Sept 2016	Optimal drag polar prediction.
Nov. 2016	Dissertation Defense.

Optimization of the apparatus for Field



Present Field Configuration

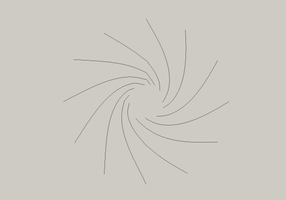


Figure: Bottom Vanes

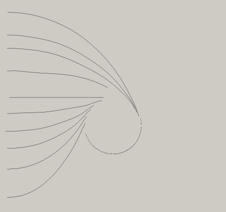


Figure: Top Vanes

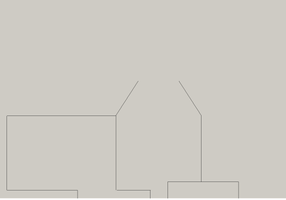


Figure: Vertical Slice

Two Tier Configuration

- Highly asymmetric second tier
- Vanes arranged to align with incoming wind
- Bottom tier asymmetric in height and angle

Present Field Results

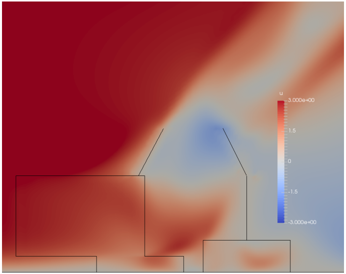


Figure: Streamwise velocity

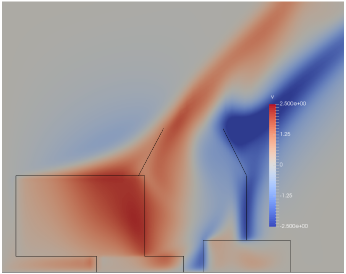


Figure: out of plane velocity

Observations

- Configuration space explored with steady Virtual Vanes
- ≈ 3 kW KE flux

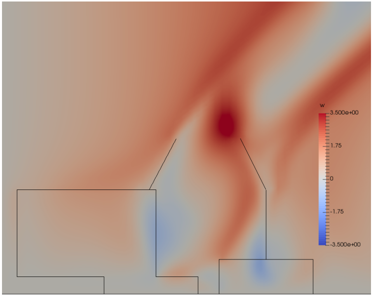
Turbine

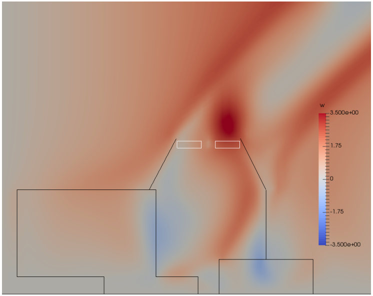
Model

- Actuator-disk
- Implementation similar to virtual vanes
- 90° circular-arc lift and drag polars (C_D, C_L)
- 7 parameters (shown below)

Name	Symbol	Comments
Initial Angle of Attack	α_0	At R_G
Final Angle of Attack	α_f	At L_B
Chord Length	C	Blade thickness
# of blades	A_B	
Center Gap	R_G	Gap in turbine
Base Velocity	ω	fixed tip velocity
Blade Radius	L_B	Length of blade
Height of turbine	H_B	Height of center of turbine

Vertical velocity field with and without turbine





Impact of the turbine (drawn in white)

- Modestly impacting flow, vortex structure largely intact
- Only extracting $\approx 30\%$ of energy
- Optimized drag polars would provide "best case" (see timeline)

Conclusions

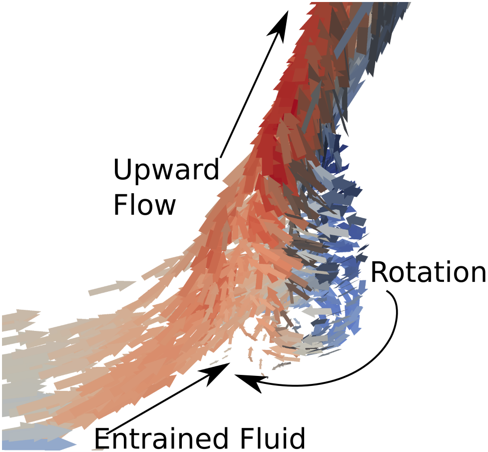
Summary

- Developed modeling approach for domain of interest
- Simulation results consistent with available measurements
- Solution structure is cyclonic, dust devil-like

Future Work

- Final optimization of apparatus
- Turbine drag polar optimization
- Field test summer 2016
- Assessment of technological feasibility
- Connection to natural phenomena (Rankine Vortex?)

The End



Thank you!

nick@ices.utexas.edu

Course list

Course #	Semester	Course Name	Instructor
ME381P	2014 Spr.	Validation & Uncertainty Quantification	Prof. R.D. Moser
ME 382R5	2014 Spr.	Advanced Combustion	Prof. O.A. Ezekoye
CSE 397	2014 Spr.	Comp. & Var. Methods for Inv. Problems	Prof. O. Ghattas
SDS 384	2014 Fall	Bayesian Statistical Methods	Prof. S. Walker
SDS 394	2014 Fall	Scientific & Technical Computing	Dr. V. Eijkhou
ME 382P	2015 Fall	Adv. Exp. Methods in Thermal/Fluids	Prof. D. Bogard

Estimate of Energy Scaling

- Medium size dust devil: 3m $=$ D, $U = 5$ m/s, $\Delta T = 30$ K, 3 meters tall
- Assume a turbulent boundary layer ($\delta = 10$ cm),

$$u(z) = U \text{ min } \left(\left(\frac{z}{\delta} \right)^7, 1 \right)$$

Boussinesq potential energy flux over the upstream flow [Renno]:

$$E_p = \int u(z)(\rho(z) - \rho_\infty) g z \, dA$$

$$E_p = g \pi R \beta \rho_0 U \Delta T \left[\frac{z_{\text{max}}^2}{2} - \frac{7\delta^2}{18} \right]$$

$$= 103 \text{ Watts}$$

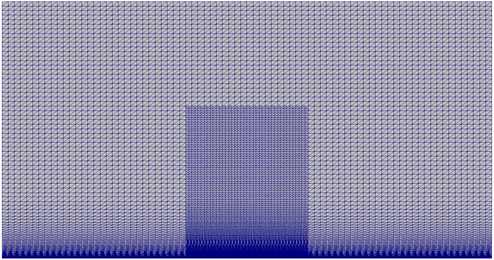
The KE flux: surface integral over upstream face of dust devil:

$$\text{KE} = \int \frac{\vec{V}^2}{2} \rho \vec{V} \cdot \hat{n} \, dA$$

$$\text{KE} = R \rho U^3 \left[z_{\text{max}} - \frac{10}{11} \delta \right]$$

$$= 1144 \text{ Watts}$$

Mesh



Discretization

- Single refinement in vane region
- $$\text{Re}_{\text{cell}} = \frac{\max(\Delta x, \Delta y) u}{\nu_T}$$
- Boundary layer mesh visible