Numerical Simulation of Synthetic, Buoyancy-Induced Columnar Vortices

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The dust devil phenomenon

Turbulent, unstable motions

- Incident solar energy absorbed into ground
  - peak solar insolation 1000 W/m^2
- Ground heats air by conduction
- Heated air expands, lowering density, driven upward by force of buoyancy
- Arizona in Summer ($\Delta T = 30$ K)
- Ubiquitous: Snow, Water, Mars
- Velocities can exceed 33 m/s.

How much power is present in one of these objects?

Power Estimate [Sinclair, Battan, etc.]

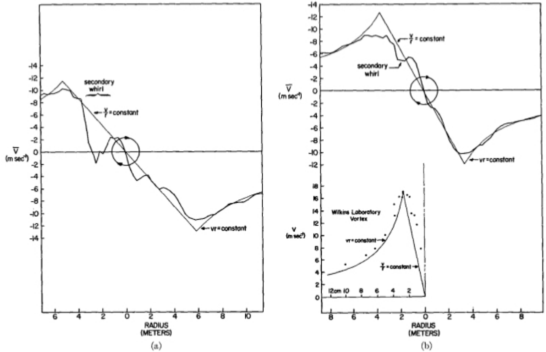
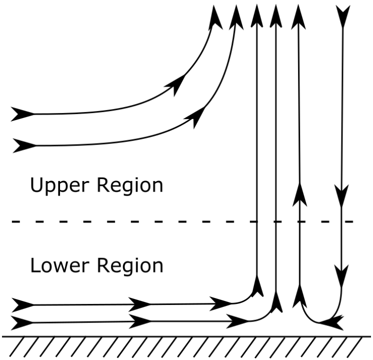


FIG. 11. Radial distribution of the mean tangential velocity at two levels, $z=7$ ft (a) and $z=31$ ft (b), for D-D #1 with superimposed Rankine combined profiles.

- Estimate from Sinclair's measured velocities
- R ≈ 5 meters, $V_\theta \approx V_z \approx 10$ m/s
- Kinetic energy flux $= \frac{1}{2}\rho \int V_z(V_z^2 + V_\theta^2)\, dA \approx 45$ kW
  - Exceeds PV per m^2

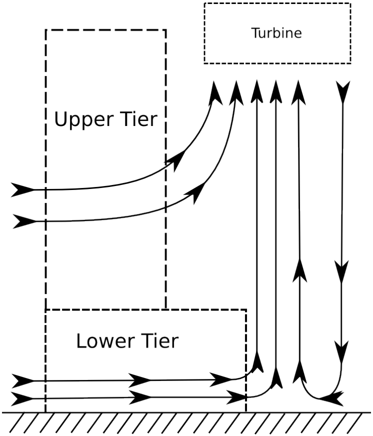
Dust Devil Structure [Sinclair,Kanak,Renno]



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
  - Artificially introduce rotation through turning vanes
  - Two tier configuration mimics natural phenomenon
  - Turbine at upper tier vanes to extract energy
- Clean
- Renewable
- Inexpensive

Project Objectives

ARPA-E

- Experimental concepts developed at Georgia Tech
- Difficult to explore design space experimentally
  - Field tests in Arizona (GT)
  - Expensive to alter configuration
  - Difficult to measure everything

Our Role

- Provide simulation-based design
- Inform design for 2016 field test
  - Probe and optimize SoV configuration
  - Predict energy output
- Feasibility Assessment
  - Is technology competitive?

Project Objectives, cont.

Outline

- Modeling
- Optimization Method
- Present Configuration and Results

Model Scenario Space

- Atmosphere, buoyancy, winds, etc.

Solar Vortex (SoV) System Configuration

- Represent complex configuration with Reduced Order Models in CFD
  - Turning vanes
  - Cone (and solid surfaces)
  - Turbine

Dynamical Equations

The equations describing fluid flow with natural convection are,

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

$$\nabla \cdot \mathbf{u} = 0$$

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

- 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!

Diffusivity Modeling

$$\begin{aligned}\nu &= \nu_l + \nu_a(z) + \nu_V(r,z),\\ K &= K_l + K_a(z) + K_V(r,z).\end{aligned}$$

Monin-Obukhov Diffusivities for Atmosphere, ν_a, K_a

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

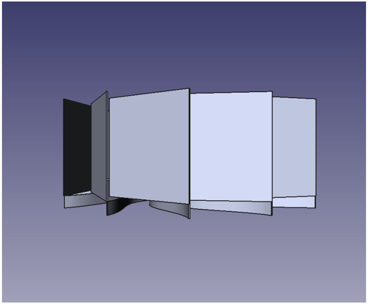
$$\bar{f} = f(z, \frac{g}{T_0}, u^*, \rho_0, \frac{q}{\rho_0\, c_p})$$

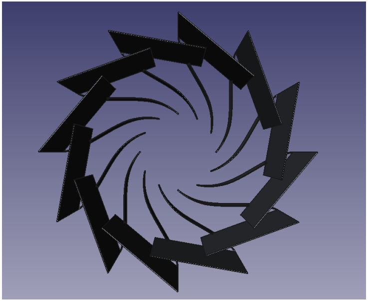
- Function of only a single non-dimensional group:

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

- Asymptotic conditions interpolated by functions
  - common to atmospheric modeling

Example configuration

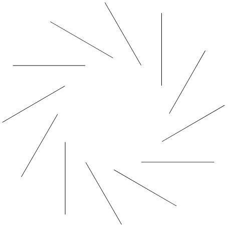


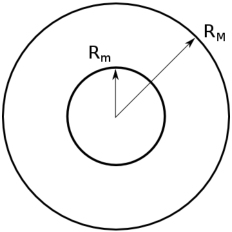


Turning Vanes

- Several 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
- A turbine is placed above the vanes to extract kinetic energy

Turning Vane Representation





Virtual Vanes

- Volumetric forcing:
  - Vane surface not represented
  - Very general formulation, no re-meshing
  - Similar to actuator-disk
- Apply $\mathbf{f_v}$ to force flow parallel to vanes,

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

Diffusivity Modeling

$$
\begin{aligned}
\nu = &\quad \nu_l + \nu_a(z) + \nu_V(r, z), \\
K = &\quad K_l + K_a(z) + K_V(r, z).
\end{aligned}
$$

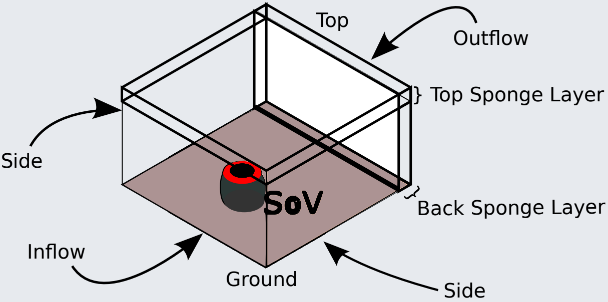
Vane Diffusivities, ν_V, K_V

- Accounts for turbulence not represented by virtual vanes
- Modeled as free shear layer, turbulent self-similar circular jet,

$$\nu_V = U_0 \, L \, C_\nu$$

- Applied only in the region interior to the turning vanes
- C_ν dimensionless constant
- L either:
  - "VLES"-like: separation distance between vanes (unsteady)
  - "RANS"-like: system diameter (steady)

Wind Cases



- Specified Inflow (Dirichlet)
- Top and Outflow have special mixed B.C.
- Sponge layers on Top and Outflow
- Natural boundaries on the side (Neumann)

Numerics

Formulation

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

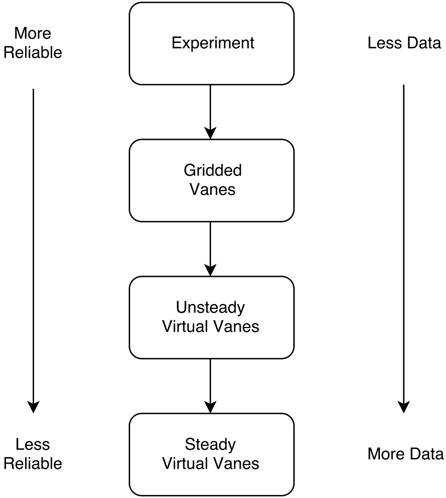
Software

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

Hardware

- Runs performed on LS4,LS5, Stampede at TACC
- 264-528 processing cores
- Several million degrees of freedom for each run, $\mathcal{O}(10^4)$/task

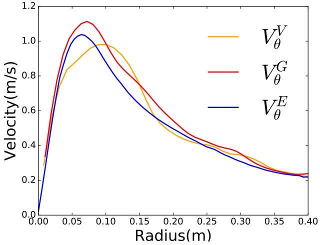
Modeling Hierarchy

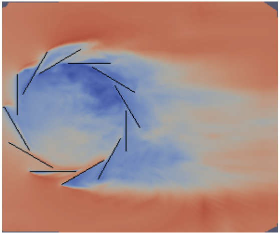


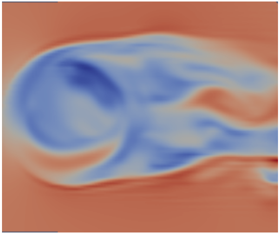
Validation

Scenarios and Configurations

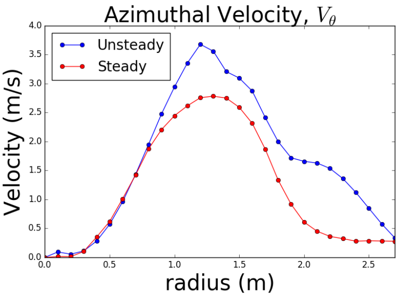
- Tabletop Laboratory
- Cold Wind Tunnel
- Field Tests
- Hierarchy of CFD models
  - Gridded vs. virtual
  - Steady vs. unsteady

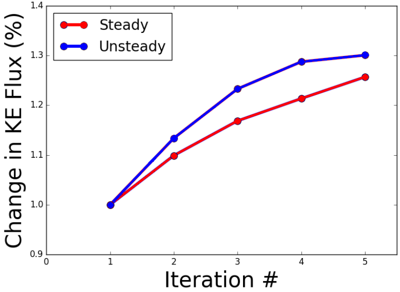






Steady vs. Transient Virtual Vanes

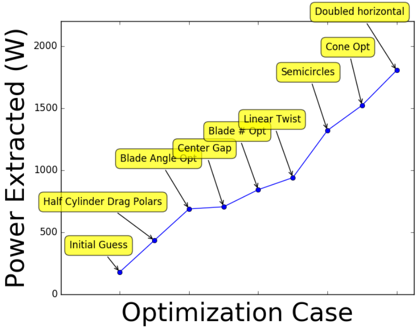




Transient vs. no $\frac{\partial()}{\partial t}$

- Captures variations in plume and wake vs. no dynamics
- Run-time 12 hrs vs. 2 minutes
- Consistent sensitivities to QoI
- Steady is principle design tool

Optimization

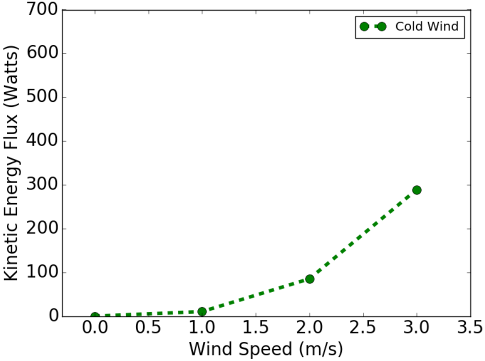


Heuristic

- Iterative perturbation of SoV system parameters
- If change in kinetic energy flux favorable, design “accepted”
- Performed for vanes, turbine, cone, etc.
  - “Circle back” to test coupling
- Several hundred iterations performed
- Energy surface complicated

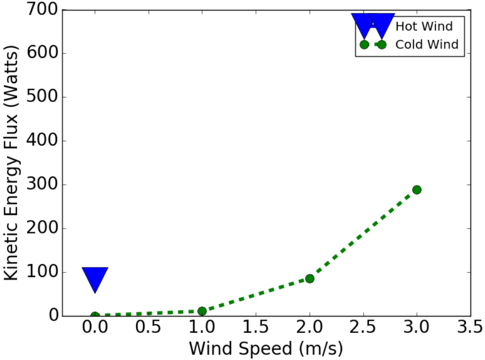
The results of this effort was used for the 2016 Field Test

Interplay between Wind and Temperature



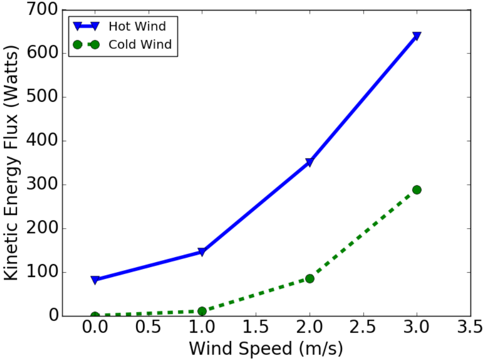
- Higher wind velocities increases energy flux

Interplay between Wind and Temperature



- Higher wind velocities increases energy flux
- Kinetic energy flux only 100 Watts in thermal-only

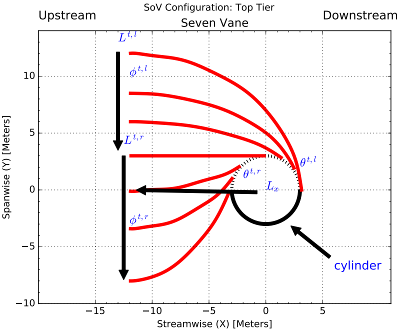
Interplay between Wind and Temperature



- Higher wind velocities increases energy flux
- Kinetic energy flux only 100 Watts in thermal-only
- Energy flux more than doubles with ΔT
    - Not just vertical axis wind turbine!

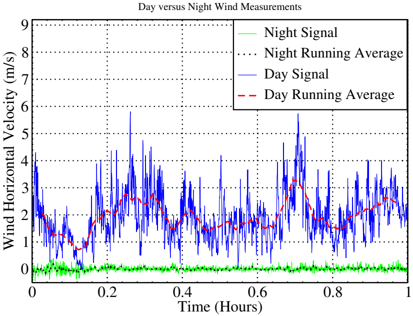
Thermal and wind are synergistic

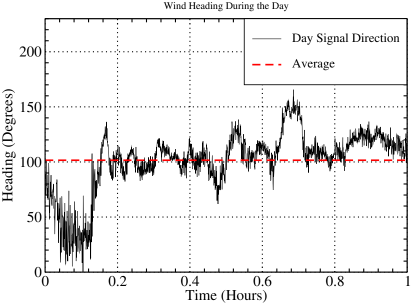
Top Tier Vanes



- Image generated by tracing through virtual vanes
- Vanes aligned with streamwise (wind) velocity
- Larger collection area upstream of device
- Impermeable half cylinder arc
- 6 meter inner diameter

Scenario Conditions

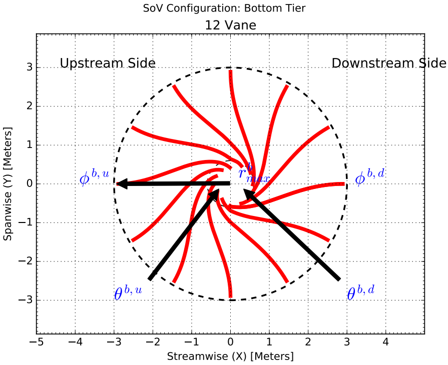




Ambient Conditions

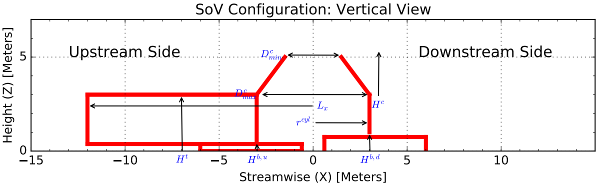
- Wind heading largely constant
- Wind magnitude steady
- Consistent with other data and regional analysis
- Thermal B.L. profile fit to field measurements

Bottom Tier Vanes



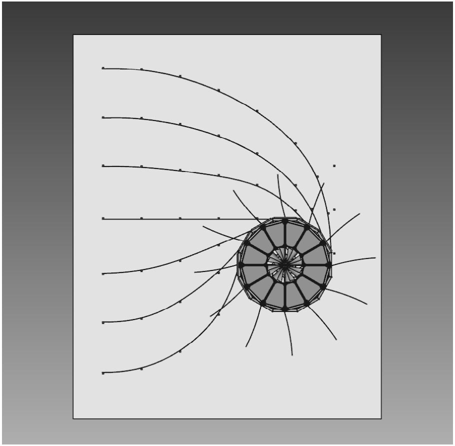
- Bottom tier vanes not symmetric along upstream/downstream sides:
  - Different heights
  - Different final angles
- Significant inflow from downstream

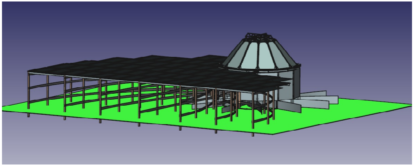
Vertical View



- Cone visible
- Height asymmetry in bottom tier vanes visible
- Turbine placed at top of cone
- Vertical partition on top of 2nd tier vanes

CAD drawings

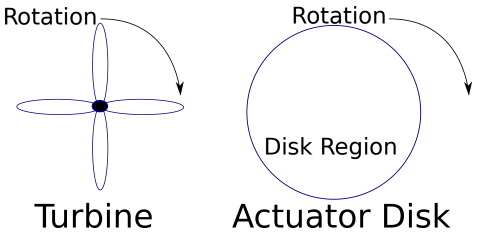




Images

- Cone clearly visible
- Horizontal Partitions
- Turning Vane Posts (drag)
- Consistent with field test
- CAD credit: John Culp, GT

Turbine Model



Actuator Disk (Blade Element Momentum)

- Represents turbine blade geometry as spinning disk
- Assumes axisymmetric turbine, neglects unsteady effects
- Not validated
- Common in wind turbine industry

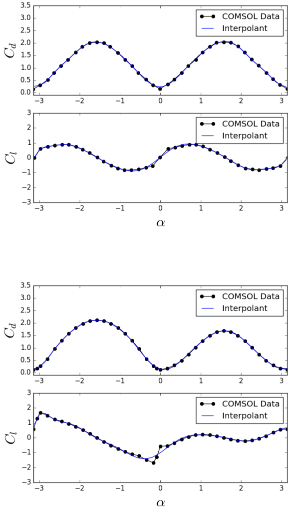
Turbine Model

BEM

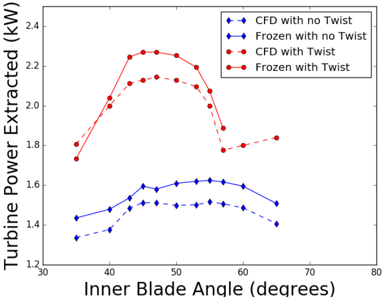
- Simple model, does not require remeshing
- Represented as a region of volumetric forcing,

$$F''' = \frac{1}{2}\frac{\rho\, B\, c\, \mathbf{u_p}^2}{\pi r t}\left(C_l\, \mathbf{n_l} + C_d\, \mathbf{n_d}\right)$$

- flat plate, 90°, 180° all considered



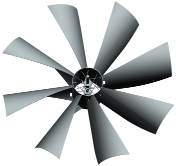
Turbine Optimization Method



Coupled Effort

- Optimization effort based on UTRC (Duane McCormick) “frozen flow” and full CFD
- Both use actuator disk model
- Frozen flow used CFD as input
- Iterative procedure
  - Frozen flow prediction
  - “Confirmed” by CFD
  - Not automated!
- Results broadly agree
  - Frozen flow assumes axisymmetric flow
  - inflow updated after several iterations

Final Turbine Design



Turbine

- Flow kinetic energy flux: 4.77 kW
- Power extracted by turbine: 2.14 kW
- Efficiency: 45%
- Turbine placed at top of vanes
  - like wind tunnel contraction, cone increases symmetry of flow
- Gap in turbine

Idealized Turbine Drag Polars

Concept

- Estimate upper limit on power that could be extracted from flow, independent of particular drag polars
- Still use actuator disk model
- Instead of 90°, 180°, generalized drag polars

$$P_L = E_\tau \int_0^{2\pi} \int_{r_{\text{min}}}^{r_{\text{max}}} U_R(r,\theta,\Omega)^2\, C_L(\phi, r)\ \sin(\phi)\, r\, dr d\theta$$

Idealized Drag Polars

- Optimization problem: what lift/drag functions maximize power?
  - Constant coefficients C_L, C_D

Idealized Turbine Drag Polars, cont.

Lift/drag functions may be expressed as,

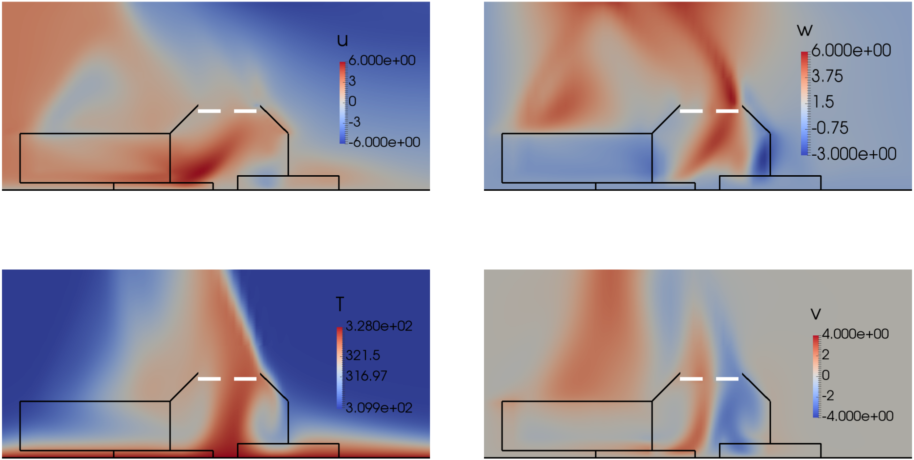
$$C_D(\phi) = \bar{C}_D\, \psi(\phi) \begin{cases} \psi(\phi) = 1 \text{ if } \sin(\phi) > 0, \\ 0 \quad\quad \text{else} \end{cases}$$

$$C_L(\phi) = \bar{C}_L\, \Psi(\phi) \begin{cases} \Psi(\phi) = 1 \text{ if } \cos(\phi) > 0, \\ -1 \quad\quad \text{else.} \end{cases}$$

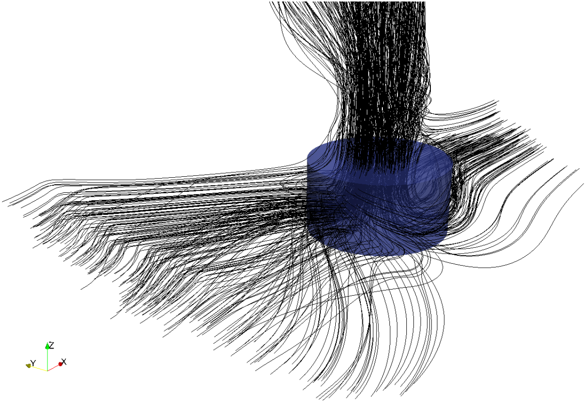
Calibration

- What constant values?
- $\bar{C}_L = 1.7$ and $\bar{C}_D = 2.0$: kills flow
- $\bar{C}_L = 1.1$ and $\bar{C}_D = 1.5$:
  - 2.76 kW vs. 2.14 kW
  - 58% efficiency vs. 45%
  - Useful for feasibility assessment

Solution Structure



Solution Structure



Particle tracking

- Entraining fluid from wide region in front of device
- Substantial backflow

2016 Field Test

What we know

- Little or no flow through device
- Configuration largely consistent with CFD

Possible Explanations

- Shading
  - ground temperature inside the vane region set to the ambient air
- Closed back vanes
  - reduced but non-zero power
- Poor field conditions
  - intermittent winds, 100° F, etc.

Several other possible model corrections were investigated

Turning Vane Drag

- Initial analysis indicated drag not significant
- Volumetric forcing applied is,

$$F''' = \hat{\mathbf{f}}\, C_f \,\frac{1}{2}\frac{\rho||\mathbf{u}||^2}{\delta}$$

- Where, the unit drag forcing vector,

$$-\frac{\mathbf{u}\cdot\hat{\mathbf{t}}^{\mathbf{v}}}{||\mathbf{u}\cdot\hat{\mathbf{t}}^{\mathbf{v}}||} = \hat{\mathbf{f}}$$

And skin friction estimated using Colebrook Formula with full roughness,

$$C_f = \left(2.0 \log\left(\frac{\epsilon/D}{3.7}\right)\right)^2$$

Turning Vane Drag, cont.

Drag Summary

- Model introduced skin-friction effects
- “worst-case” scenario
  - Drag computed based on smallest distance between vanes
  - Roughness elements based on post size
- Kinetic energy flux never reduced by more than 12%.
- Crude model indicates reduced flows not attributable to drag

Solidity Modification

Observations

- Little or no flow observed in turbine region
- Number of blades (8) larger than typical wind turbines (2-3)
- Hypothesis: flow “blocked” by large and numerous turbine blades

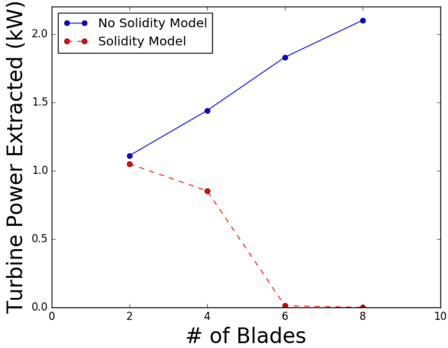
Actuator Disk Modification

- Actuator disk neglects interaction effects between turbine blades
- Correction to forcing by reducing flow area,

$$B(r) = 1 - \frac{l_B(r)}{2\pi r}$$

  Ratio: l_B (length blocked by turbine blades) vs. total area
- As l_B increases, velocity vector will align with drag

Solidity Modification



Correction to actuator disk

- Model assumes flow separates from turbine blade
  - "worst case" estimate
- Six and eight turbine blades greatly impacted
- Even with correction, model appears inadequate
- Need calibration/validation data for more detailed assessment
  - Data needed from field or gridded simulation

System Feasibility Assessment

Not competitive with other renewable sources

- Order of magnitude less power for same 6 meter diameter

Additional Risks

- No validation
- Solutions are “Fragile”
  - changes to turbine, vanes, etc. resulted in substantial decreases in power extracted

Additional Questions

- Independent of economic assessment (e.g. kW$/\$$)
- Why is energy flux predicted in SoV lower than dust devils?

Conclusions and Future Work

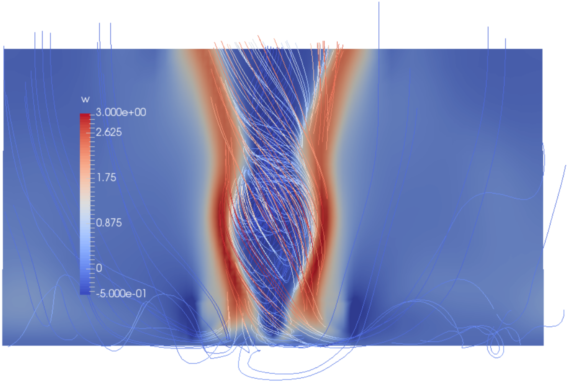
Contributions

- SoV results not promising
- Turning vane formulation (and separation, drag models)
- Solidity modification for actuator disk
- Steady models and optimization heuristic for exploring configurations
- Idealized drag polars
- Simulations indicate that experiments generating dust devil-like structures

Future Work

- Application in different scenarios (waste heat, etc.)?
- Turbine design using actuator disk for non-traditional flows
- Tool to simulate dust devils?

The End



Thank you!

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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]:

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

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

$$= 217 \text{ Watts}$$

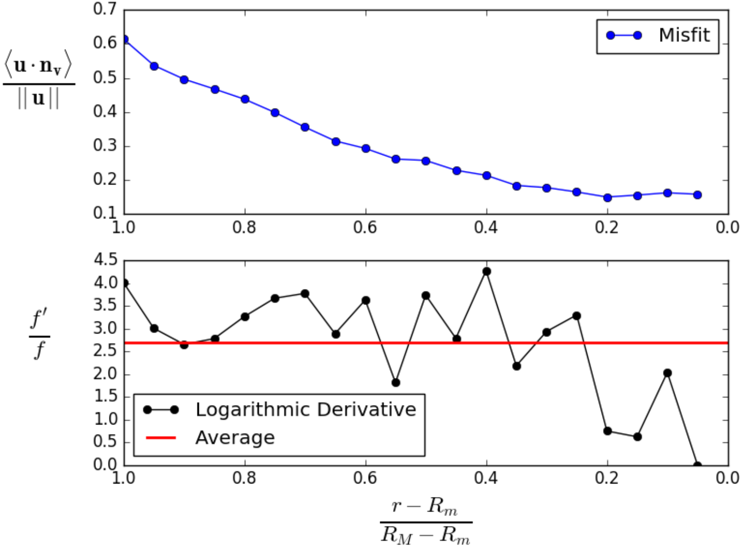
The KE flux: surface integral over upstream face of dust devil:

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

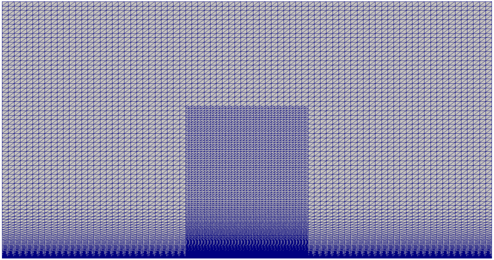
$$\text{KE} = R \rho U^3 \left[z_{\text{max}} - \frac{10}{11} \delta \right]$$

$$= 1144 \text{ Watts}$$

Calibration of Virtual Vanes



Mesh



Discretization

- Single refinement in vane region

$$\text{Re}_{\text{cell}} = \frac{\max(\Delta x, \Delta y)\, u}{\nu_T}$$

- Boundary layer mesh visible

Stabilization Outline

- Cast Navier Stokes + Boussinesq equations into weak form
- Prepare as operator $Lc = f$
- Calculate Fréchet derivative (to calculate operator adjoint)
- Separate into differential (P) and constant (Z) components, $L'[c] = P + Z$
- Choose stabilization operator such that $S = -P^*$
- Then stabilization has form, $a_h(c, \phi) = a(c, \phi) + \langle Lc, S\phi \rangle_\tau$

Simulation Geometry and Boundary Conditions

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,

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

Ground

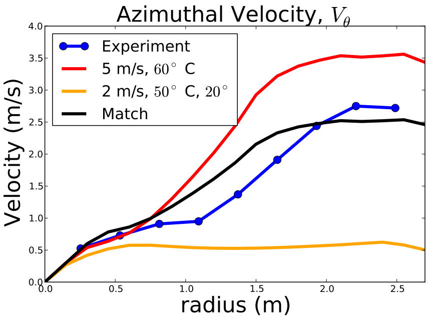
- modeled with a Dirichlet boundary condition such that,

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

2015 Field Validation Study

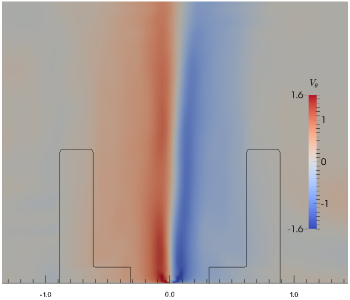
Scenario parameter uncertainty

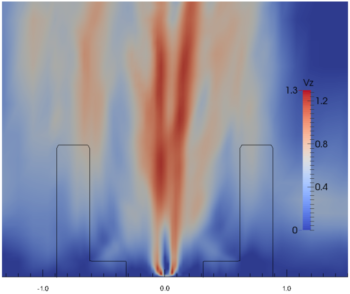
- Wind speed: 2-5 m/s
- Wind direction($\approx 20^\circ$)
- $T_\mathrm{s} = 50 - 60^\circ$ C ($\approx 121 - 140^\circ$ F)
- No boundary layer temperature data (DAQ equipment malfunctioned)

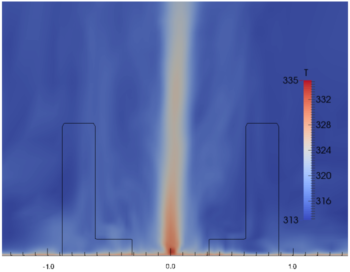


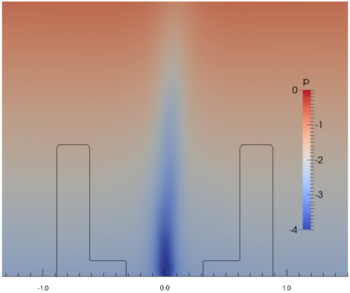
- CFD broadly consistent with field observations
  - Experimental data extremely limited
- Kinetic energy fluxes match to within 10%

Thermal-Only Structure

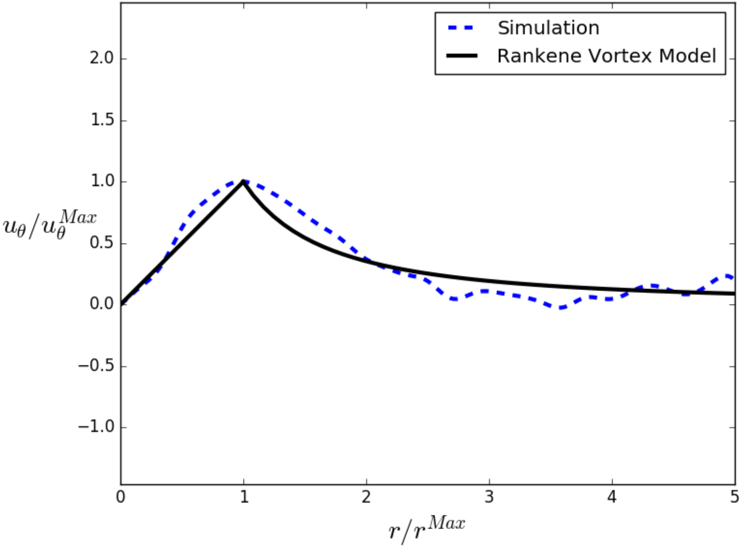








Thermal-Only Structure



Proposal 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.

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