Flow Modeling and Testing of ESPs

ICESP 2018
Charlotte, NC, USA

Robert Mudry, P.E.
Airflow Sciences Corporation
Livonia, MI, USA
rmudry@airflowsciences.com
Outline

- Introduction
- ESP Fluid Flow Basics
- Flow Modeling
  - Physical scale
  - CFD
- Questions
ESP Fluid Flow Basics

- Primary goal: Maximize particulate capture

*Image: Gerry Klemm, Southern Company*
ESP Fluid Flow Basics

Flow Related Goals

- Uniform gas velocity through collection fields
- Equal flow balance between multiple chambers
- Avoid hopper re-entrainment
- Avoid particulate deposition / drop out
- Minimize peak velocities / erosion
- Minimize pressure drop
- Uniform temperature distribution
- Sorbent injection / mixing
Gas Velocity Distribution

- Uniform velocity within collection region

- Industry standards
  - ICAC
  - RMS/CV deviation

ICAC:
- 85% of velocities $\leq 1.15 \times V_{avg}$
- 99% of velocities $\leq 1.40 \times V_{avg}$

Other:
- % RMS Deviation $\leq 15\%$ of $V_{avg}$
Gas Flow Balance

- ICAC goal: flow within ±10% per chamber

Percent of total mass flow through each chamber:
- 21%
- 35%
- 26%
- 18%

ICAC: Flow within each chamber to be within ±10% of its theoretical share
Hopper Re-entrainment

- Avoid gas flow in hoppers
- Avoid sweepage

Particles escape due to gas flow in hopper

Image: Gerry Klemm, Southern Company
Particulate Deposition

- Duct floors
- Turning vanes
- Perforated plates
Particulate Deposition

- Extreme deposition $\equiv$ structural failure
Peak Velocities / Erosion

- Erosion potential depends on
  - Impact velocity (to the 2.5 power)
  - Flow rate
  - Hardness, shape
  - Angle of impact

- Erosion issues
  - Vanes
  - Baffles
  - Perforated plates
  - Ductwork
  - Trusses
Pressure Drop

- General goal:
  - Minimize DP

Ductwork redesign saves 2.1 IWC (520Pa)
Gas Temperature

- Temperature stratification
  - Resistivity
  - Corrosion
  - Sorbent performance
Injection Systems

- Gaseous injection
  - SO3, NH3, others

- Particulate injection
  - Activated carbon
  - Trona, SBS, lime, etc.
Sorbent Injection

- Goals
  - Uniform distribution
  - Surface contact / residence time
  - Mixing / dispersion
ESP Modeling

- Physical Model Testing
- Computational Fluid Dynamics (CFD)
ESP Modeling – Physical Models

- Background
- Theory
- Simulation Parameters
- Fabrication Details
- Results Analysis
- Flow Visualization
Physical Models – Background

- Utilized for fluid flow analysis for a century … or more?
- Applied to ESPs for decades
- Underlying principle is to reproduce fluid flow behavior in a controlled, laboratory environment
Physical Models – Theory

- Key criteria is to generate “Similarity” between the scale model and the real-world object
  - Geometric similarity
    - Accurate scale representation of geometry
    - Inclusion of all influencing geometry elements
    - Selection of scale can be important
  - Fluid dynamic similarity
    - Precise Reynolds Number (Re) matching is not feasible
    - General practice is to match full scale velocity but ensure that Re remains in the turbulent range throughout the model

\[
Re = \frac{\rho v D_h}{\mu}
\]
Physical Models – Parameters

- **ESP geometry**
  - Typically 1/8th to 1/16th scale
  - Include features affecting flow patterns

- **Flow conditions**
  - Scaled air flow rate (at ambient temperature)
  - Simulate injections with a tracer gas
  - Simulated particle tracking
    - In flight
    - Deposition
Physical Models – Fabrication Details

- More detail is better
  - Vanes, splitters, baffles
  - Trusses, gusset plates
  - Dampers, columns
Physical Models – Fabrication Details

- Perforated plate selection
- Collection plate representation
  - Geometry / loss coefficient
  - Re consideration
Physical Models – Results Analysis

- **Quantitative data**
  - Available at discrete measurement points
  - Velocity magnitude, directionality
  - Pressure (corrected to full scale)
  - Tracer gas concentration
  - Mass balance between chambers
  - Comparison to ICAC conditions
  - Correlation to test data

- **Qualitative data**
  - Flow directionality (smoke, tufts)
  - “Dust Test” for particle behavior, drop-out, re-entrainment
Physical Models – Velocity Results

- Uniformity vs. ICAC goals

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Velocity (ft/s)</td>
<td>8.5</td>
<td></td>
</tr>
<tr>
<td>%RMS Uniformity</td>
<td>12.1%</td>
<td>&lt;15%</td>
</tr>
<tr>
<td>% of points &lt;115% of average</td>
<td>90.7%</td>
<td>&gt;85%</td>
</tr>
<tr>
<td>% of points &lt;140% of average</td>
<td>100.0%</td>
<td>&gt;99%</td>
</tr>
<tr>
<td>% of lower 25% of area &gt;71% of average</td>
<td>100.0%</td>
<td>&gt;99%</td>
</tr>
</tbody>
</table>
Physical Models – Dust Testing
Physical Models – Visualization

- Smoke flow
- Helium bubbles

Images: Gerry Klemm, Southern Company
Physical Models – Visualization

- Video footage
ESP Modeling – CFD

- Background
- Theory
- Simulation Parameters
- Mesh Details
- Results Analysis
- Flow Visualization
CFD – Background

- Developed in the aerospace industry c.1970 (with the advent of “high speed” computers)
- Applied to ESPs for 30+ years
- Underlying principle is to solve the first-principles equations governing fluid flow behavior using a computer
CFD – Theory

- **Control Volume Approach**
  - Divide the flow domain into distinct control volumes
  - Solve the Navier-Stokes equations (Conservation of Mass, Momentum, Energy) in each control volume

ESP model with 12,500,000 cells

Control Volume or “Cell”
CFD – Mesh Details

- A good mesh is critical for accurate results
  - Cell count
  - Length scale
  - Local refinement
  - Shape/topology
    - Hex vs. Tet vs. Poly
  - Flow alignment

- Why?
  - Finer resolution = more accurate results
  - Numerical calculation scheme accuracy is influenced by cell topology
Not all CFD cells are created equal

- Hexahedral vs. Tetrahedral vs. Polyhedral
- Tet mesh = easier, automeshing
- Hex or hybrid mesh = harder, hand built
- 5 million Hex cells = 30 million Tet cells

Hexahedral cell (6 faces)

Tetrahedral cell (4 faces)

6 Tet cells fit into 1 Hex cell of the same length scale
CFD – Mesh Details

- **Direct geometry inclusion**
  - Vanes, baffles
  - Structure

- **Numerical simplification**
  - Perforated plates
  - Collection plates
CFD – Simulation Parameters

- **ESP geometry (mesh)**
  - Full scale representation
  - Include features important to flow, more detail if possible

- **Flow conditions**
  - Full scale gas flow rate
  - Reproduce velocity & temperature profile at model inlet
  - Simulated chemical injection
  - Simulated particle tracking

- **Solver**
  - Azore
  - Fluent
  - Star CCM+
CFD – Results Analysis

- Quantitative data available at all control volumes
  - Velocity magnitude, directionality
  - Temperature
  - Pressure
  - Turbulence
  - Chemical species concentrations
  - Particle trajectories

- Integrated/reduced data
  - Mass balance between chambers
  - Comparison to ICAC conditions
  - Correlation to test data
CFD – Results

- Velocity patterns
- Uniformity vs. ICAC goals
  - All cells vs. traverse
- Pressure drop
CFD – Advanced Modeling

- Electrostatics
- Transient phenomenon
- Large meshes and HPC solvers
- Pressure pulses during to rapping
  - Hopper “splash”
  - Minimizing re-entrainment
- Chemistry / absorption

Image: Gerry Klemm, Southern Company
CFD – Flow Animations

- Video footage
Model Correlation – Field Testing

- Velocity Distribution in ESP
  - Cold flow conditions
  - Vane anemometer
    - Rides on plates / electrodes
    - Accuracy 1% in 3-10 ft/sec range
    - Lightweight, portable
    - Sensitive to flow angularity, turbulence, dust
  - Difficult, expensive test
Field Testing – Collection Region

- Accuracy can be influenced by
  - Proximity to perforated plate
  - Collection plate geometry
  - Electrode geometry

- Scrutinize the test data closely
Flow Model Accuracy

- Do physical and CFD models provide useful results, suitable for ESP design?
  - Yes, experience has shown that modeling is a dependable engineering tool
  - Useful for new ESPs and improving existing ESPs
  - Needs to be performed correctly and to the best of current modeling practices
Flow Model Accuracy

- Do the model results match actual plant data?
  - Not as well as one would like in some cases
  - Error bars are larger than desired
  - Correlation can be dependent on ESP geometry
    - Nozzle style inlets are particularly challenging for models
    - Square and ladder vane style inlets have stronger correlation

- What to do when they don’t match?
  - Re-evaluate the modeling, improve the methods
  - Scrutinize the test data
Flow Model Accuracy

- Do CFD and physical models match each other?
  - Sometimes but not all
  - Correlation of uniformity statistics vs. profile
  - Limitations of both methods hamper correlation
  - Can be dependent on ESP geometry
    - Inlet style – nozzle vs. square
    - Flow devices and complexity
  - Research is ongoing
  - Speaker’s experience in this area focuses on
    1. Perforated plate representation
    2. Collection plate representation
Summary – Industry Experience

- Hundreds of successful projects industry wide
  - Performance guarantees met
  - Reduced emissions / DP / maintenance
  - Field verification not often performed

- Improved modeling methods would allow for additional ESP performance optimization
Summary – Key Takeaways

- Both CFD and physical modeling have been widely used for decades
- From a general view, the modeling methods provide beneficial engineering tools for design
- Both methods have specific procedures, and need to be done correctly to yield usable results
- Both methods have their limitations, their supporters, and their critics
- Research is ongoing on both methods, striving to improve accuracy and correlation
Acknowledgements

- Dan Fahrer, DTE Energy
- Gerry Klemm, Southern Company
- Dr. Jia Mi, Southern Company
- Jose Sanchez, EPRI
Questions?
Contact Information

Airflow Sciences Corporation
12190 Hubbard Street
Livonia, MI  48510-1737  USA
Tel. +1.734.525.0300

Robert G. Mudry, P.E.
President
rmudry@airflowsciences.com

www.AirflowSciences.com
www.AzoreCFD.com
www.AirflowSciencesEquipment.com