Numerical Investigations on Influences of Ambient and Geometric Parameters on SALSCS Performance

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Center for Filtration Research

University of Minnesota

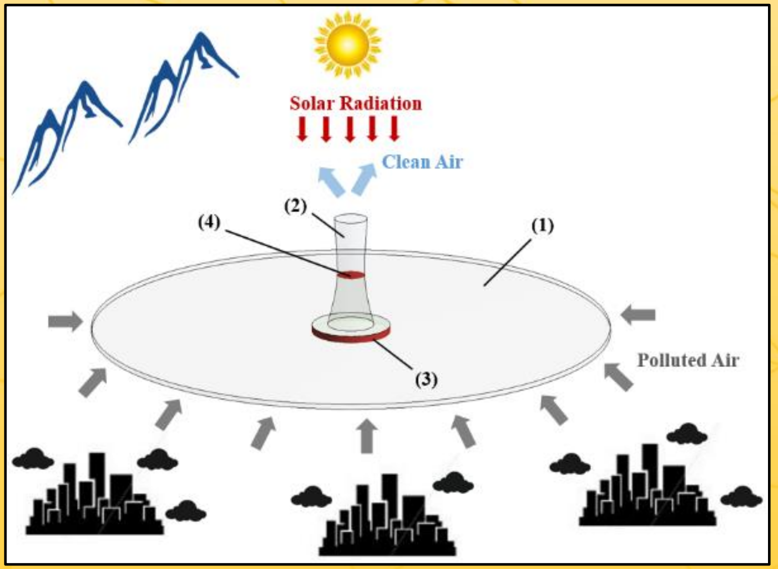
Outline

- Introduction
- Experimental measurements on the Xi’an demonstration unit for model validation
- Numerical model for SALSCS
- Parametric studies on system performance
- Summary
- Future work

Introduction

- Many urban areas experiencing air pollution problems
- Most strategies for air pollution
  - ✓ Cutting air pollutant sources (Wang *et al.*, 2017)

Schematic diagram of the full-scale SALSCS: (1) solar collector, (2) tower, (3) filtration elements, and (4) fans



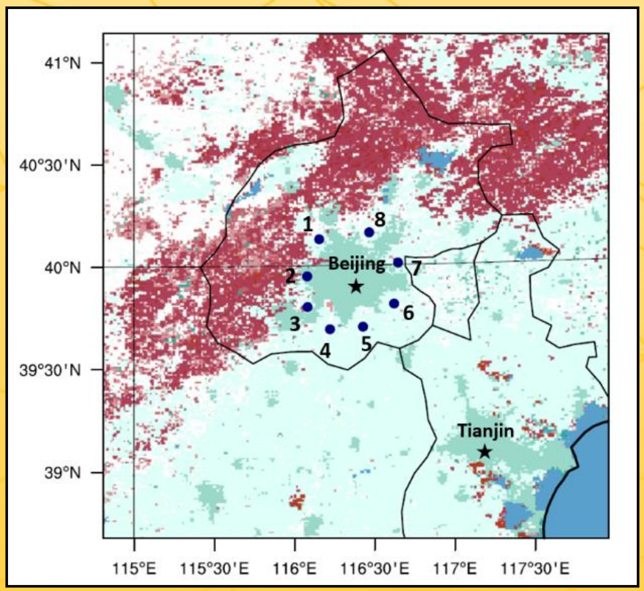
- Solar-Assisted Large-Scale Cleaning System (SALSCS) (Cao *et al*., 2015)
- Utilizing renewable solar energy to generate updraft airflow
- Sharing similar configuration with Solar Chimney Power Plant (SCPP).
- Air pollutants are then removed by filtration elements.

Cao, Q., Pui, D.Y.H. and Lipiński, W. (2015). A Concept of a Novel Solar-Assisted Large-Scale Cleaning System (SALSCS) for Urban Air Remediation. Aerosol Air Qual. Res. 15: 1-10.

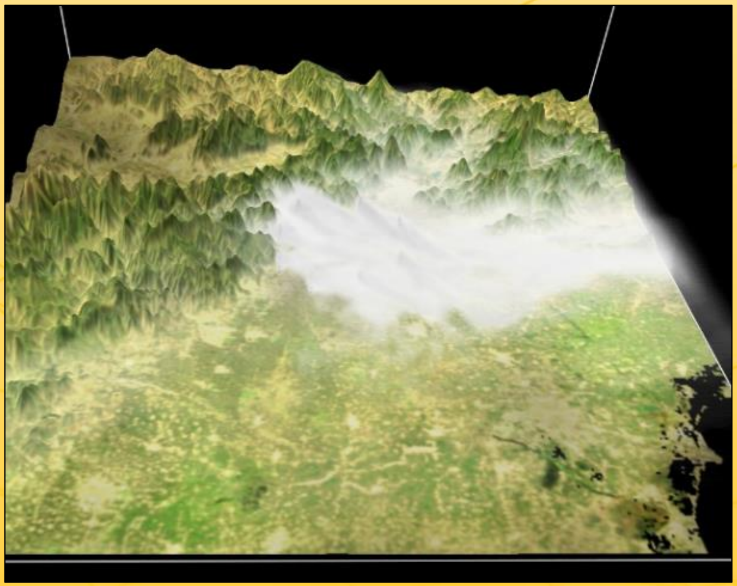
Introduction

- Atmospheric simulations over Beijing using the Weather Research and Forecasting (WRF) model (Cao *et al*., 2018)
- Eight full-scale SALSCSs installed in the suburb
- Up to 15% of $PM_{2.5}$ concentration can be reduced

Land use distribution in WRF model



Snapshot of 3D visualization of SALSCS clean air plumes

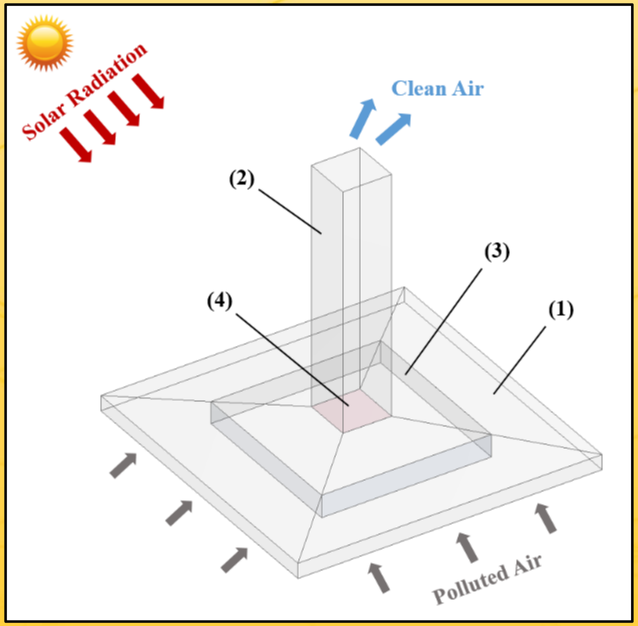


Cao, Q., Shen, L., Chen, S.-C., and Pui, D.Y.H. (2018). WRF Modeling of $PM_{2.5}$ Remediation by SALSCS and Its Clean Air Flow Over Beijing Terrain. Sci. Total Environ. 626: 134-146.

Introduction

- To improve SALSCS's performance
- Reducing system's dimensions
  - ✓ Solar collector and tower dimensions of between 10 m -120 m
  - ✓ Installed inside city blocks
- Parametric studies on system performance
  - ✓ Ambient parameters
  - ✓ Geometric variables
- To provide guidance for system design

Schematic diagram of the urban-scale SALSCS: (1) solar collector, (2) tower, (3) filtration elements, and (4) fans



Field Measurements on the Xi’an Demonstration Unit

- A demonstration unit of SALSCS in Xi’an.
  - ✓ A solar collector of 43 × 60 m^2 in horizontal dimensions
  - ✓ A tower of 60 m in height.

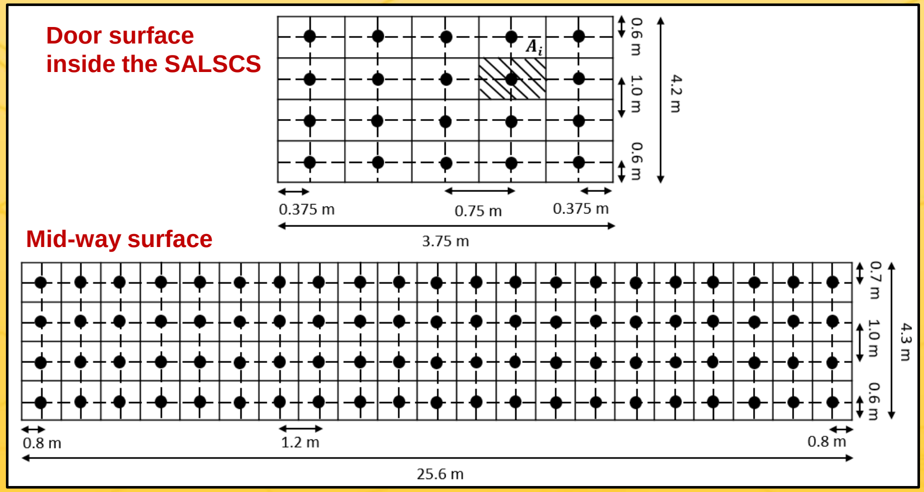
Photos of the Xi’an demonstration unit

Field Measurements on the Xi'an Demonstration Unit – Cont.

- Experimental measurements conducted in Jan 2017
  - ✓ system flow rate
  - ✓ temperature
- Ambient parameters were recorded

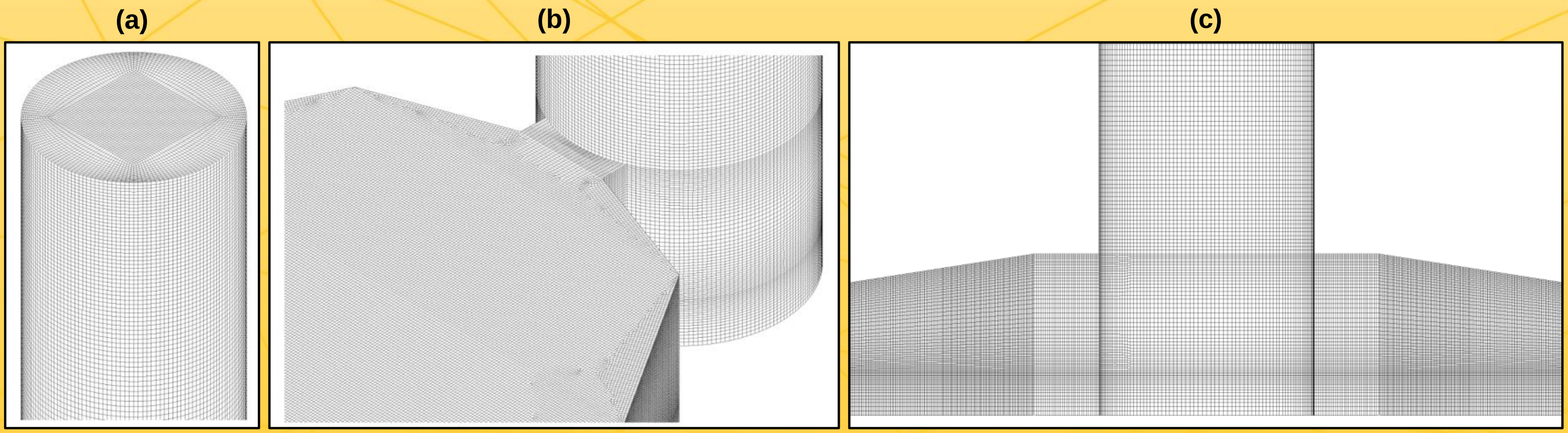
Photo showing the two measuring surfaces

Layout of the measuring points at the two measuring surfaces



Numerical Model for SALSCS

- Incompressible air with Boussinesq approximation for buoyancy-driven flow
  - ✓ Variation of air density ignored
- Meanwhile, 3D Reynolds-Averaged Navier Stokes (RANS) equations solved for mean velocity field for the turbulent flow
- *k*-*ε* two-equation turbulent model for Reynolds stress closure

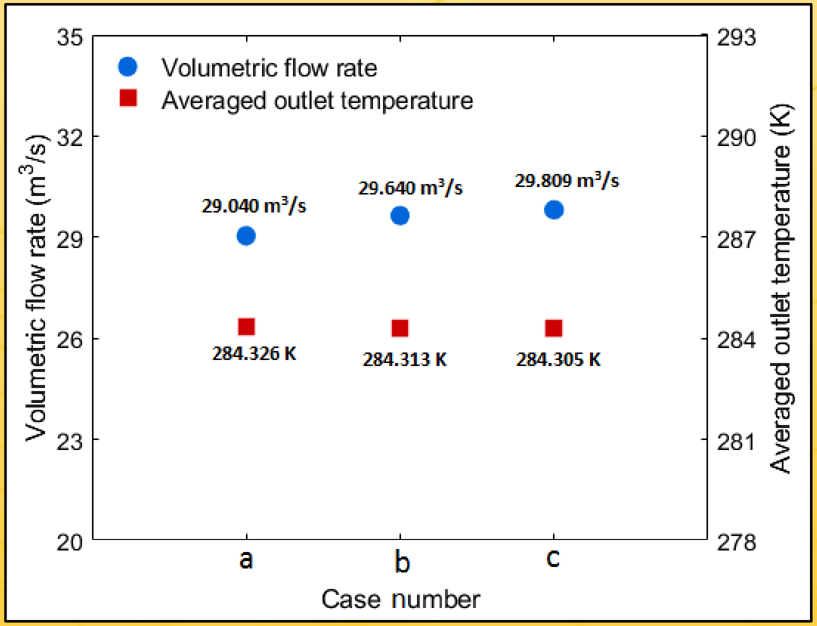


Meshing distribution of the numerical model for Xi'an Demonstration Unit: (a) grid distribution near the tower outlet, (b) grid distribution near the solar collector outlet and (c) grid distribution near the tower bottom region

Grid-Independent Study

- To determine if grid number affecting numerical results strongly
- Three simulation cases with different grid numbers
  - ✓ Case a: 1,791,987
  - ✓ Case b: 3,587,072
  - ✓ Case c: 5,416,302
- Discrepancies of 0.769 m^3/s in volumetric flow rate and 0.021 K in temperature
- Good grid-independence performance
- Case b was chosen for the study

Grid-independence performance of the numerical model

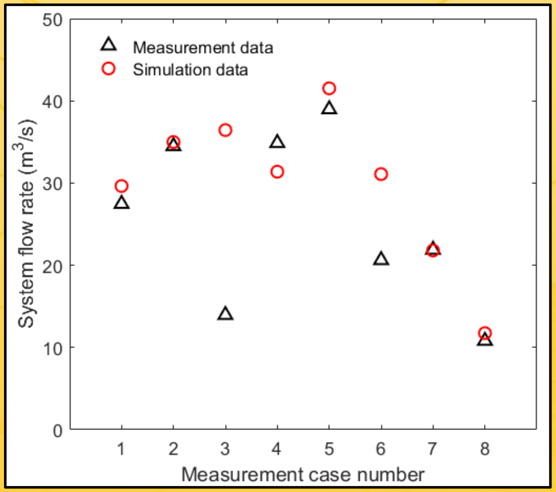


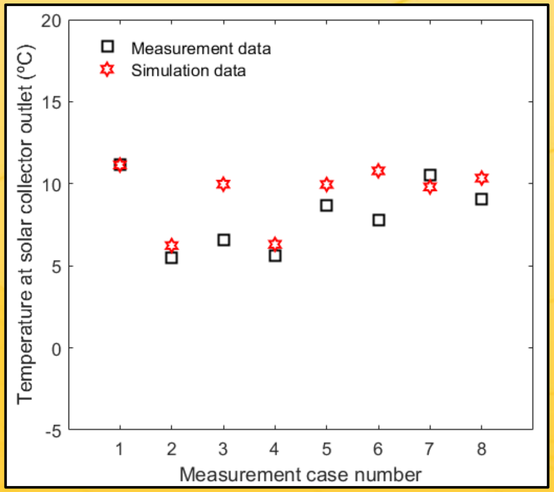
Comparison Between Measurements and Simulations

- Discrepancies for six cases
  - ✓ 1.63 m^3/s for the system flow rate
  - ✓ 0.78 ºC for the temperature
- Cases 3 and 6
  - ✓ Numerical results larger than experimental data
- The larger discrepancies appear in the north section
- Shadows from opaque structures blocked away much sunlight
- Larger ambient solar radiation being measured

✓ ***Numerical model validated***

Comparisons of numerical results and measurement data on system flow rate and temperature at solar collector outlet

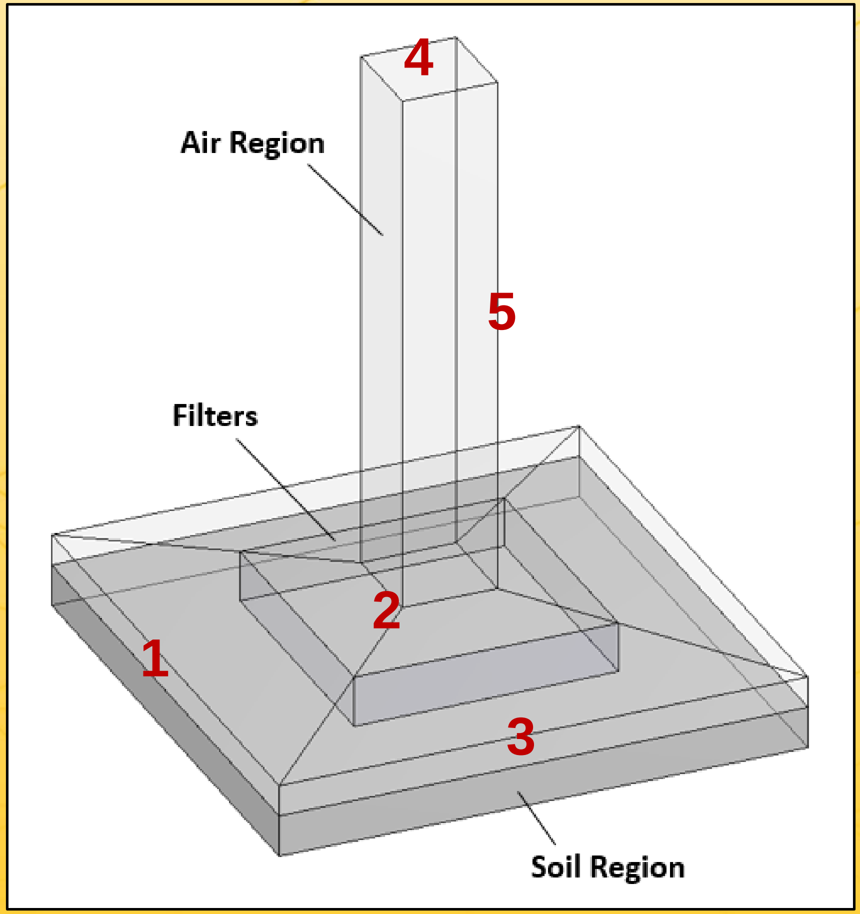




Parametric Studies on System Performance

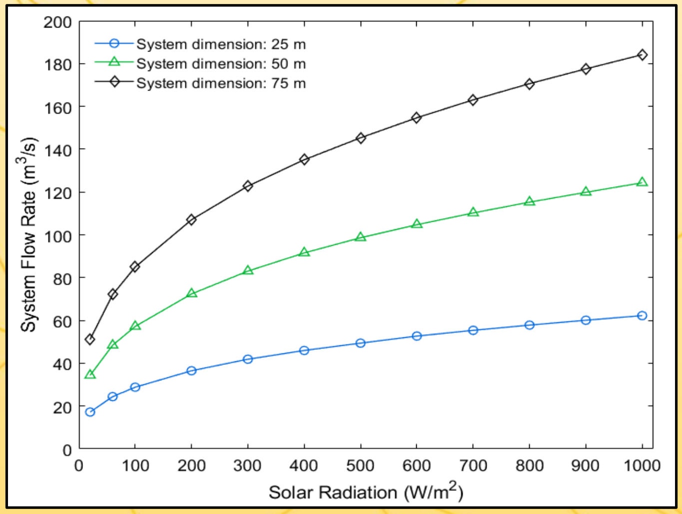
- The validated numerical model was applied
- The geometry in the current study
  - ✓ Square solar collector (10 m -120 m)
  - ✓ Rectangular prism tower (10 m -120 m)
- Five geometric variables
  1. collector inlet height
  2. collector outlet height
  3. collector side length
  4. tower side length
  5. tower height
- Ambient parameters
  1. Solar radiation
  2. Ambient air temperature
  3. 2-m depth soil temperature

Geometry of an urban-scale SALSCS with a 2-m thick soil layer underneath.

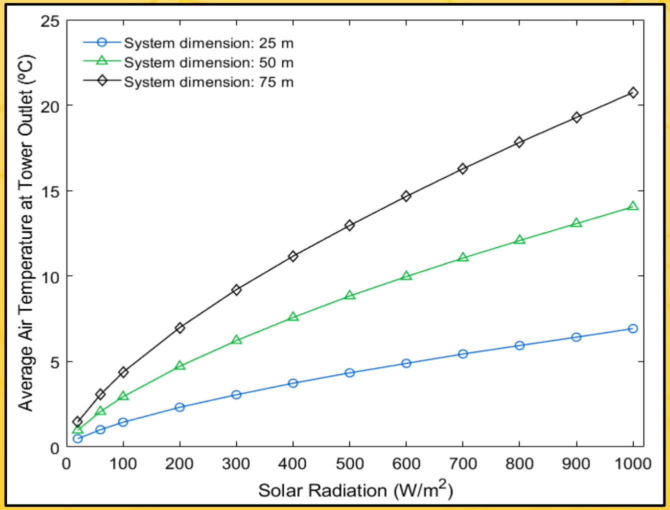


Influence of Solar Radiation

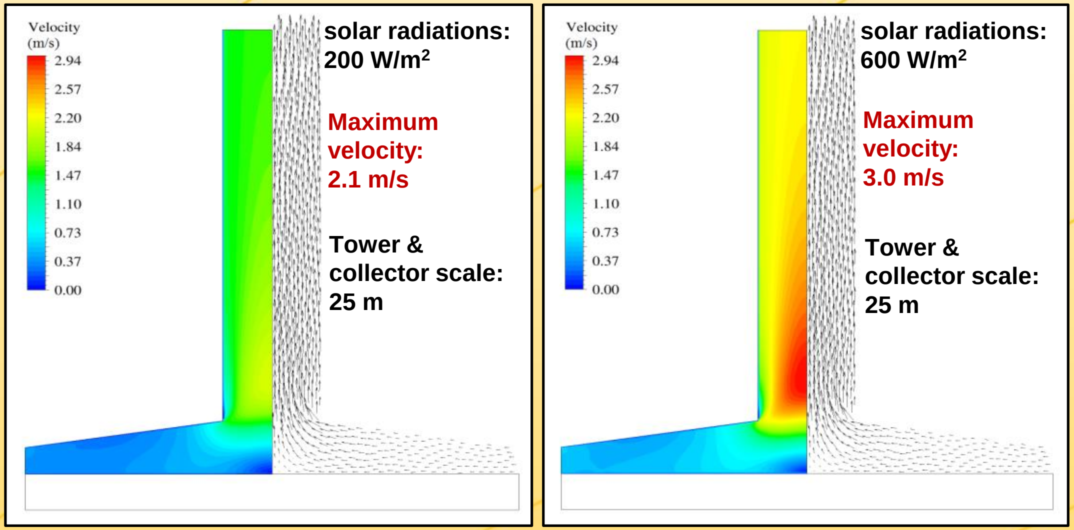
Effects of solar radiation on flow rate



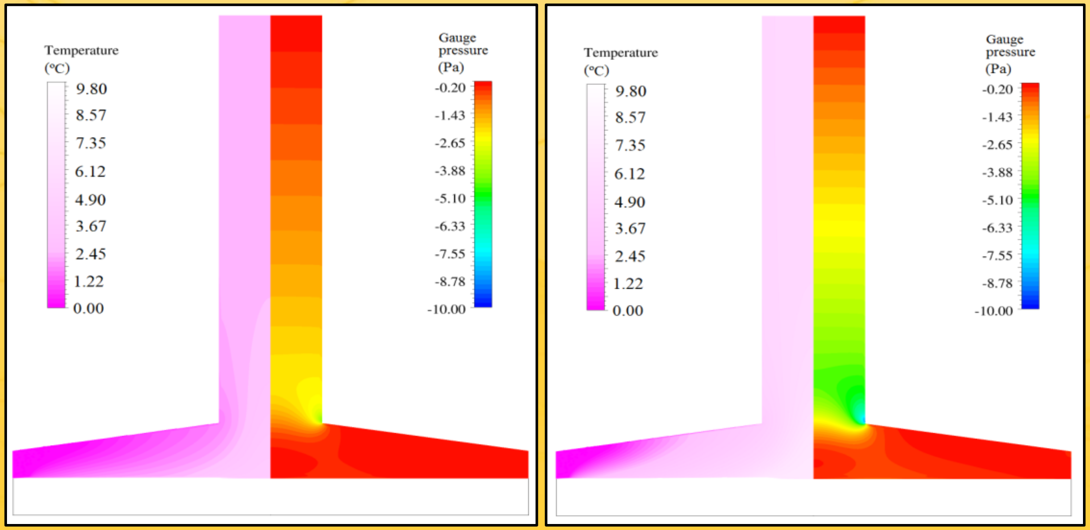
Effects of solar radiation on temperature at tower outlet



Contour and vector plots for velocity fields



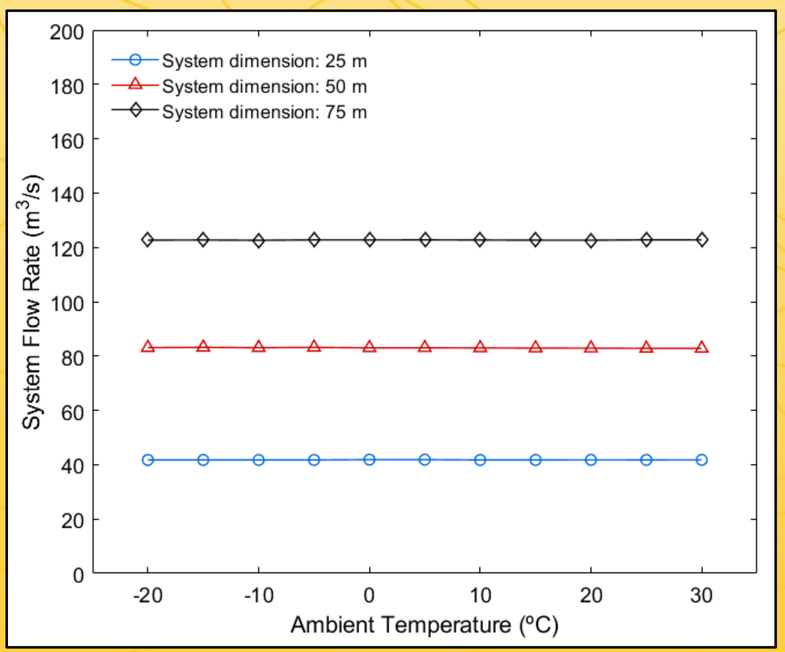
Contours plots for temperature and pressure fields



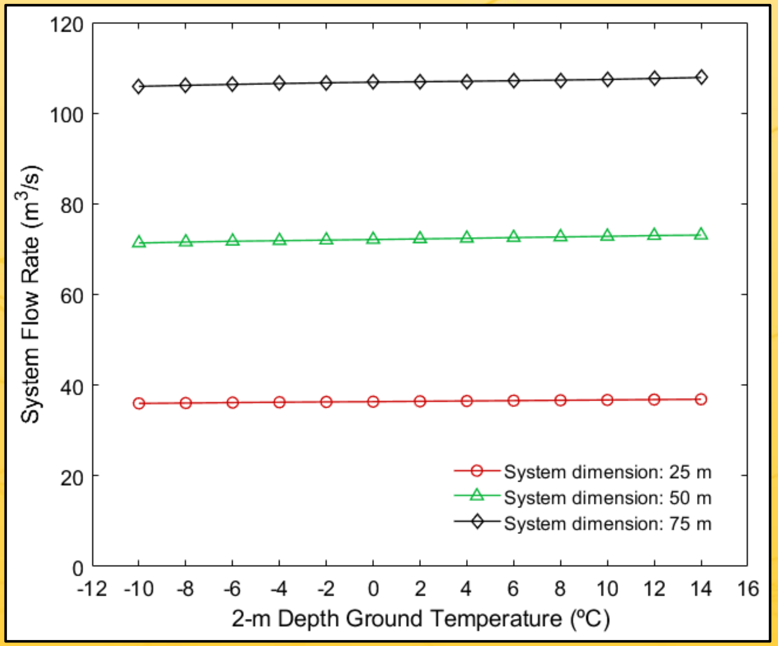
Influence of Ambient and 2-m Depth Soil Temperatures

- Small effects on system flow rate
- System airflow mainly driven by the temperature difference between inside airflow and outside ambient environment
- ✓ **Solar radiation is the dominant factor**

Effects of ambient temperature on SALSCS flow rate



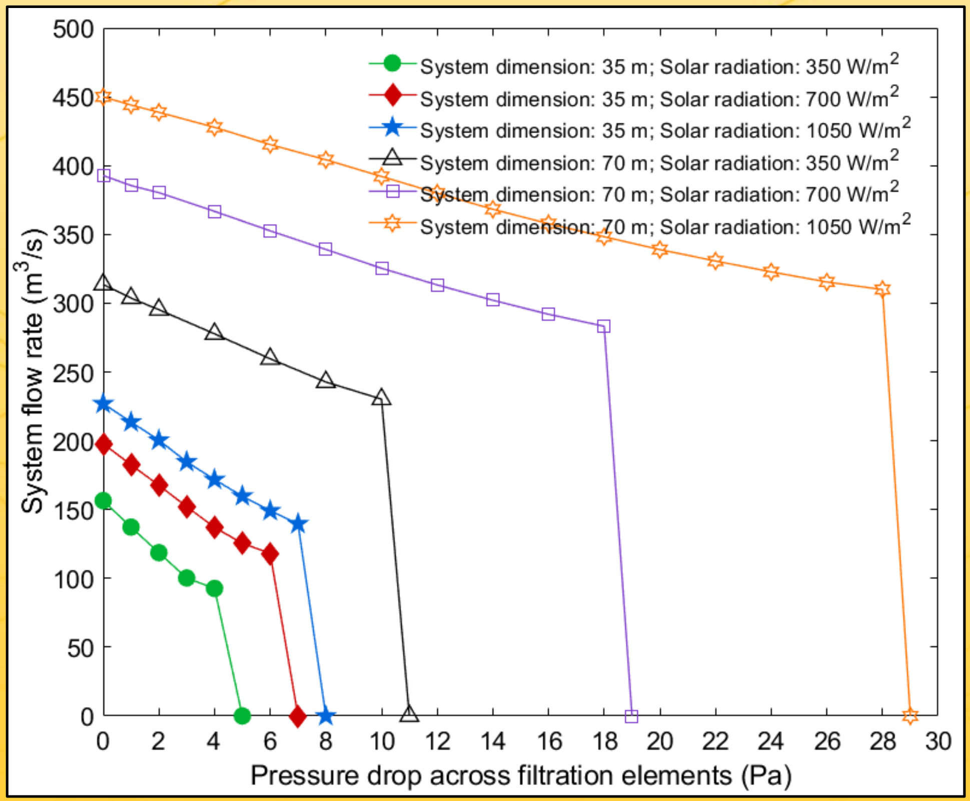
Effects of 2-m depth soil temperature



Effects of Pressure Drop Across Filtration Elements

- Filters modeled as an interface with constant pressure drop in solar collector
- Flow rate decreases almost linearly
- Critical pressure drop exists
- To overcome filters with higher pressure drop
  - ✓ Larger system dimensional scale
  - ✓ Higher solar radiation
  - ✓ Installing fans

Effect of filter pressure drop across filters on system flow rate



Influence of Tower Height

- **The higher the tower, the stronger the flow field**
- How to explain it theoretically?
- Assuming SALSCS is only a cylinder in the atmosphere with cross-section area *A* and height *H*
- Buoyancy force $B = \rho_\infty g(A \cdot H)$
- Gravitational force $G = \rho_a g(A \cdot H)$
- Driven force $F = B - G = (\rho_\infty - \rho_a) g (A \cdot H)$
- Pressure difference driving the airflow

$$\Delta p = \frac{F}{A} = (\rho_\infty - \rho_a) gH$$

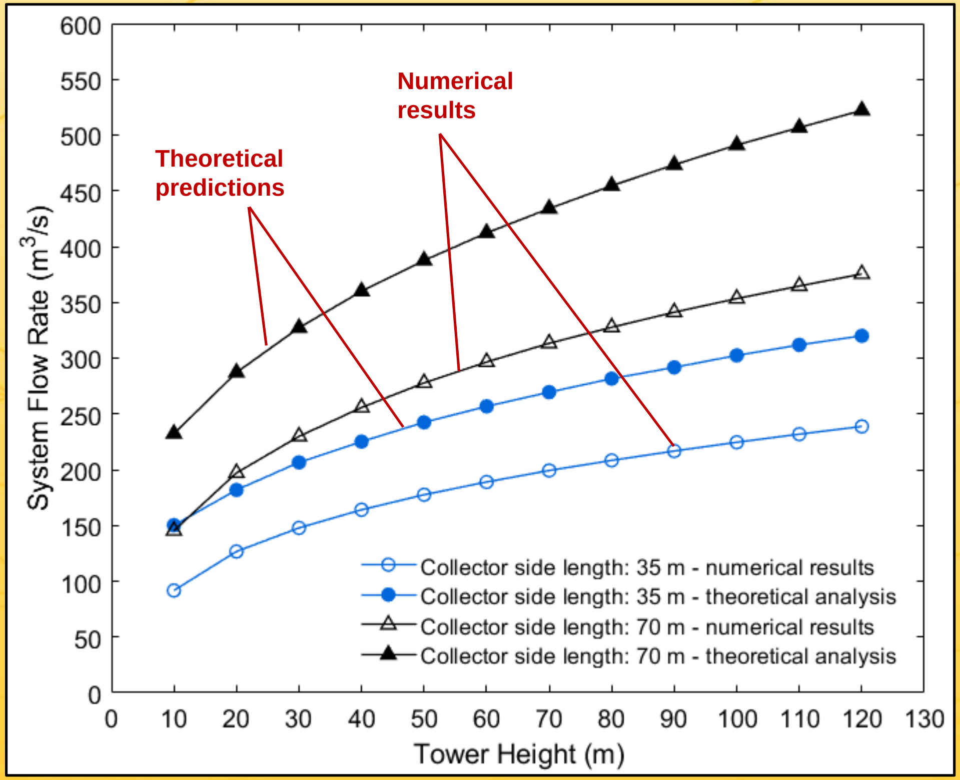
- According to Bernoulli's principle

$$\Delta p = \frac{1}{2}\rho_a v^2$$

$$v = \sqrt{\frac{2\Delta p}{\rho_a}} \xrightarrow{\text{Flow rate}} \boxed{Q = A \cdot v = A\sqrt{\frac{2\Delta p}{\rho_a}} = A\sqrt{2gH\frac{(\rho_\infty - \rho_a)}{\rho_a}}}$$

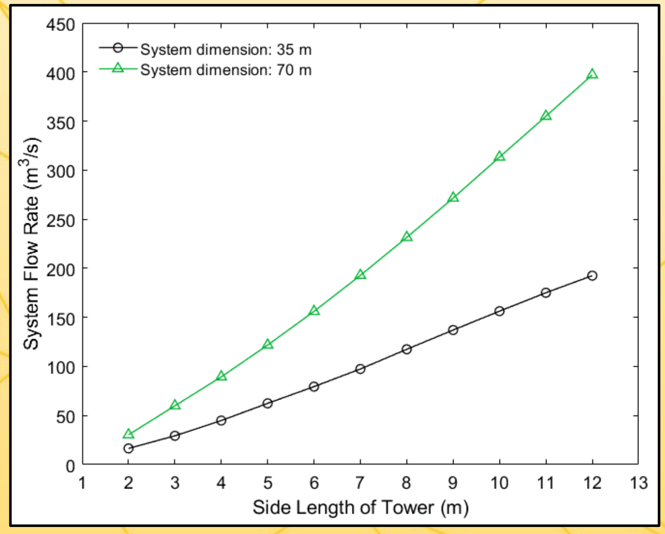
- **Similar trend**
- Higher value for theoretical results
  - ✓ Ignoring friction losses on walls

Effects of tower height on system flow rate

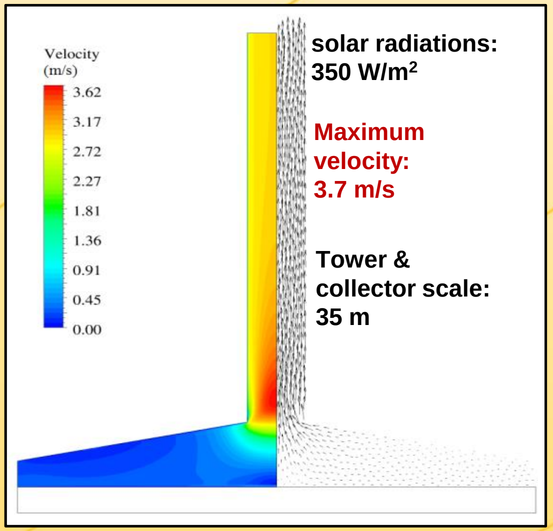


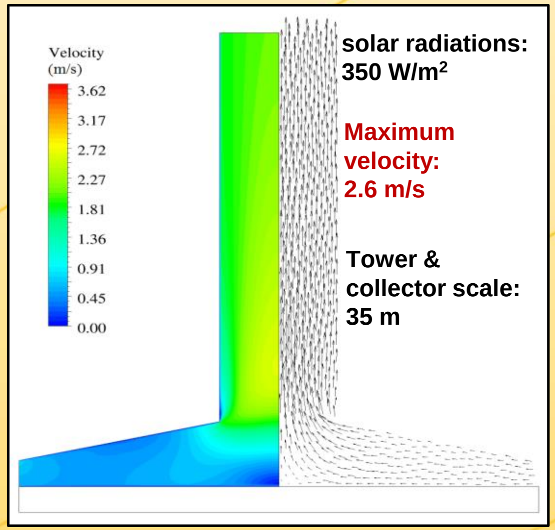
Influence of Tower Side Length

Effects of tower side length on flow rate

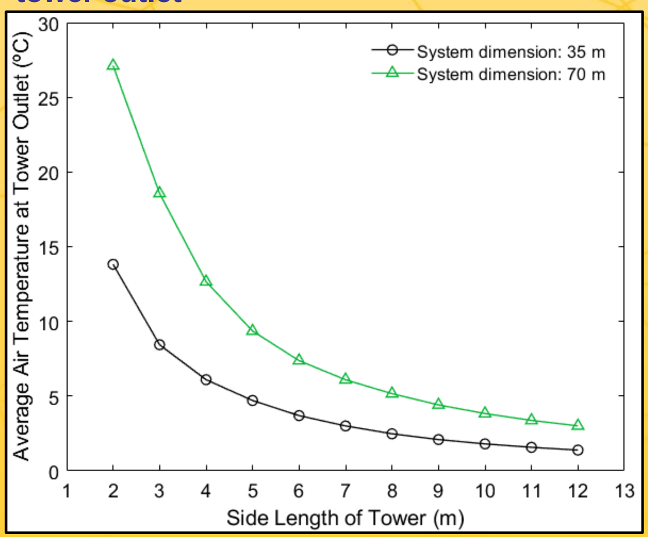


Contour and vector plots for velocity fields

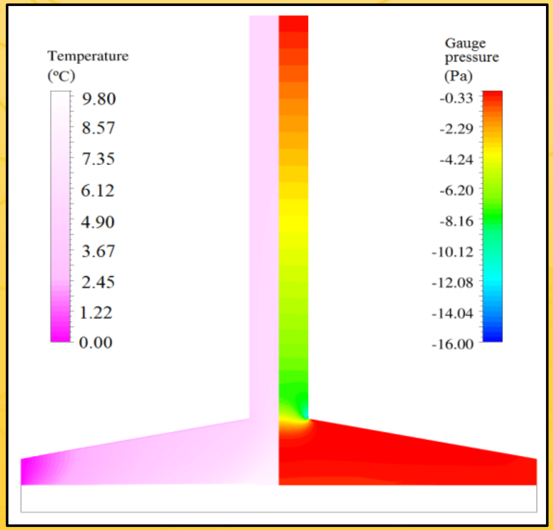


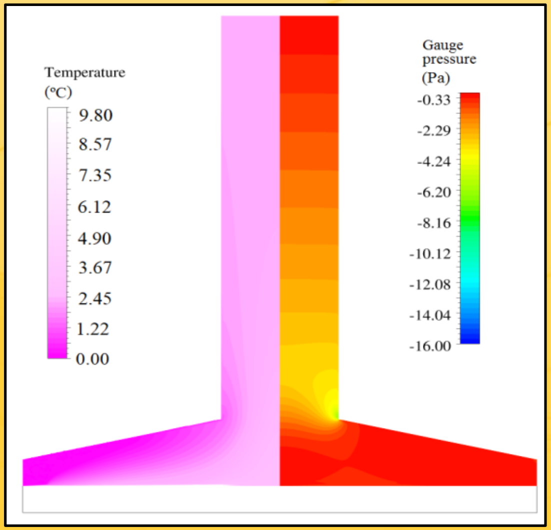


Effects of tower side length on temperature at tower outlet



Contours plots for temperature and pressure fields

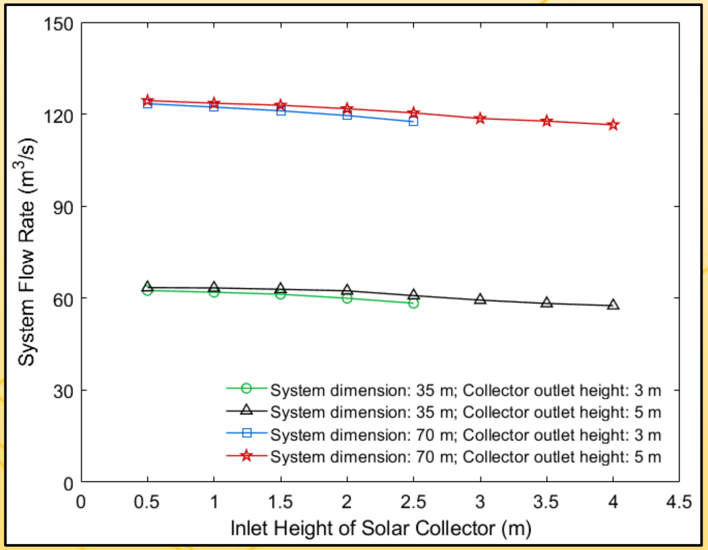




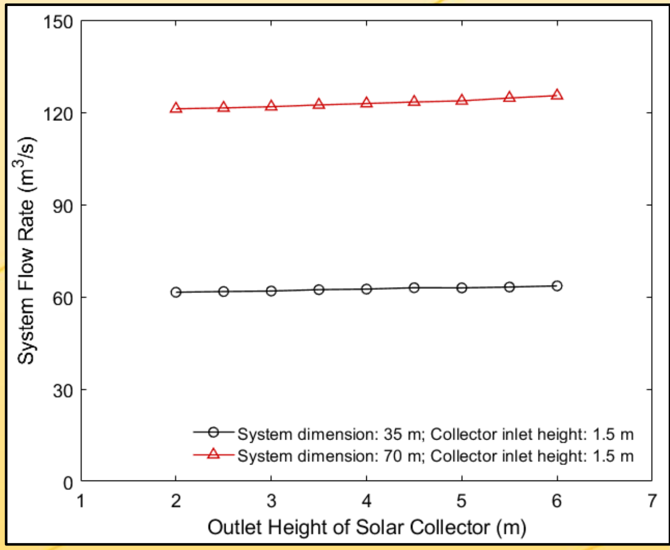
Influence of Solar Collector Dimensions

- Ratio of collector outlet to inlet height
- Higher ratio provides less drag effect
  - ✓ Higher flow rate.
- Larger collector side length
  - ✓ Higher flow rate
  - ✓ Higher temperature
- A larger collector needs more space
  - ✓ Not economic

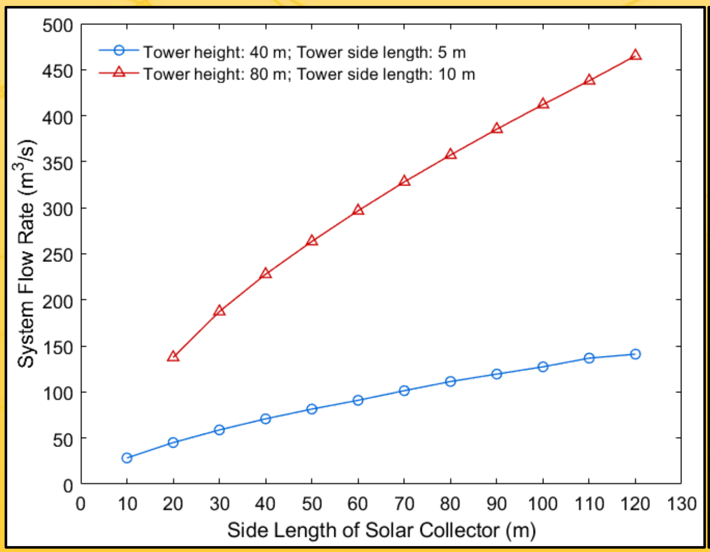
Effects of collector inlet height on flow rate



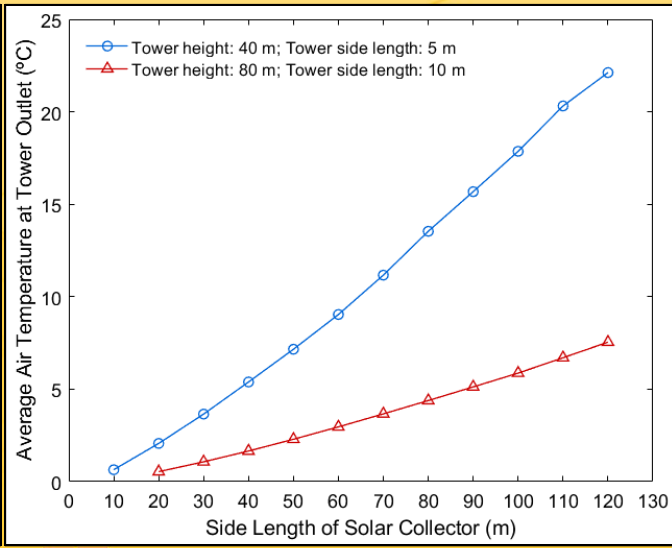
Effects of collector outlet height on flow rate



Effects of collector side length on flow rate



Effects of collector side length on temperature



Summary

- Field measurements conducted on Xi'an demonstration unit
- Numerical model developed for SALSCS in scale of 10 m -120 m
- Numerical results show good agreement with experimental data
  - ✓ Model validation

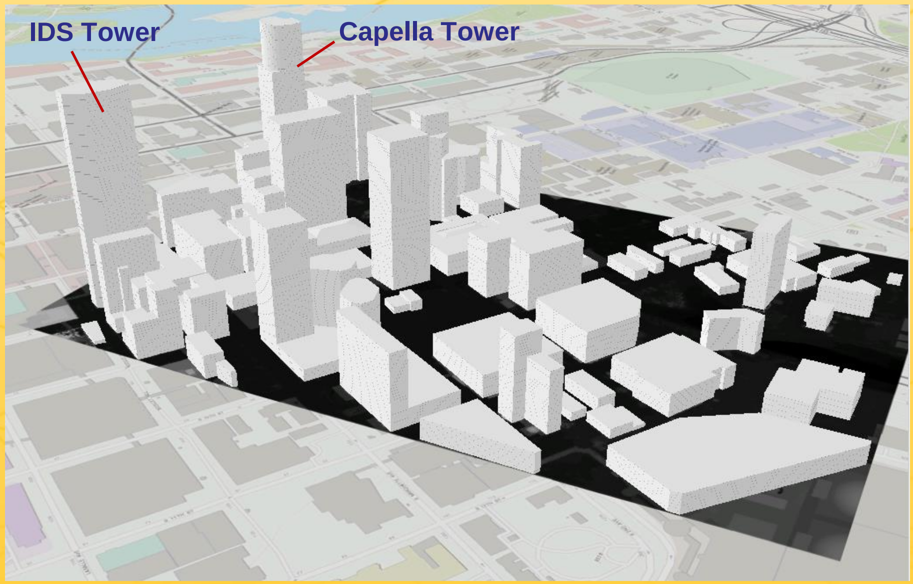
- Effects of ambient and geometric variables on SALSCS performance investigated
- Parameters with important influence identified
  - ✓ Solar radiation
  - ✓ Pressure drop across filters
  - ✓ Tower height
  - ✓ Tower side length
  - ✓ Collector side length

Future Work

- Developing a new atmospheric model with real urban topographies
- Large-eddy simulation (LES) technique
  - ✓ Large-scale motions computed directly
  - ✓ Small-scale motions modelled

3D urban topography obtained for downtown Minneapolis

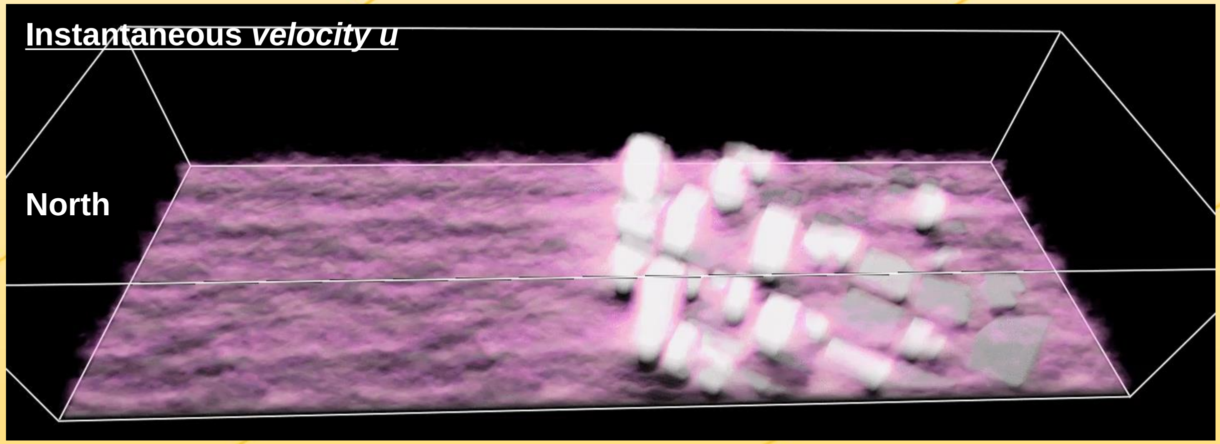
- **Two tallest building of Minnesota included**
  - ✓ **IDS Tower (245 m)**
  - ✓ **Capella Tower (237 m)**

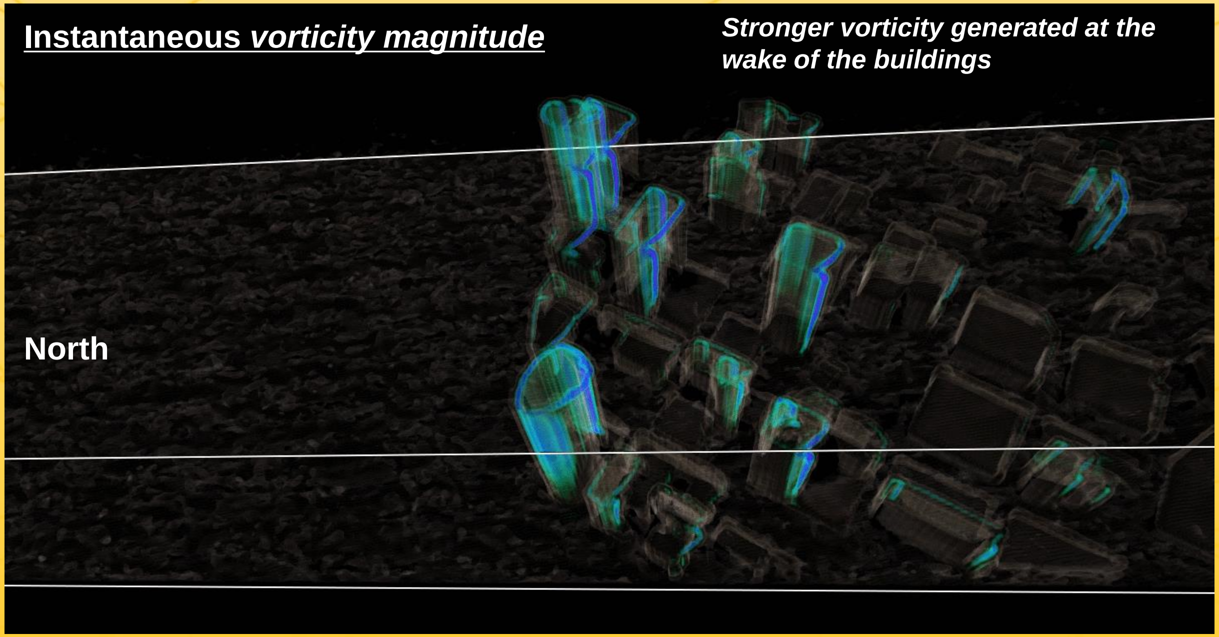


Future Work

- Velocity fields with detail structures resolved
- Air pollutants to be simulated
  - ✓ Passive scalar
  - ✓ Particle-laden flow
- SALSCSs to be implemented into city blocks
- To make better animations for flow visualization

✓ **<u>To determine their performance in removing air pollution</u>**





Thank You!

Questions?