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Toward algebraic modeling of natural convection inside simplified energy storage systems

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BACKGROUND

Large-scale energy storage systems (ESSs) show promise in addressing current energy challenges, but heat dissipation strategies need to be considered for the performance and safety of ESSs. Heat transfer via natural convection is generally not the primary cooling strategy but becomes important during module overheat or thermal runaway when batteries exhibit prolonged periods of elevated temperatures. Accurate and fast-running models of heat propagation during this time would provide ESS designers and operators better opportunities to develop strategies to minimize damage during such system failures.

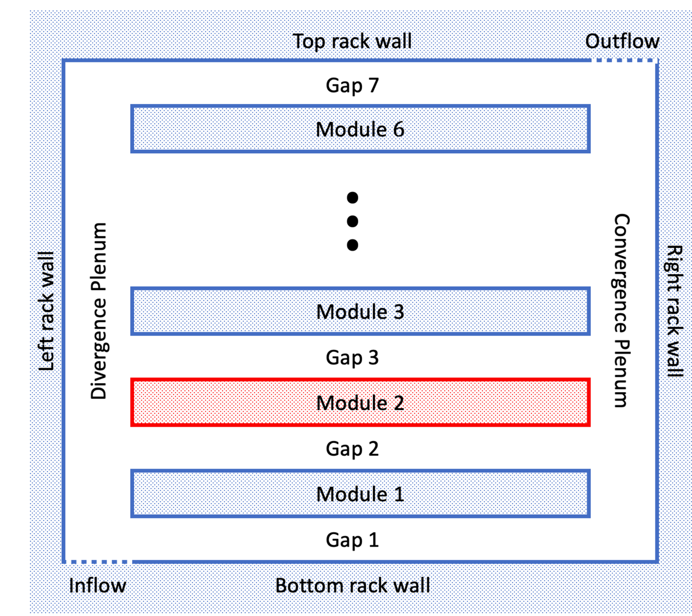
OBJECTIVE

To use computational fluid dynamics simulations of a simplified parameterized rack design to investigate the flow dynamics and heat transfer mechanisms, and to perform detailed analyses that will enable the development of fast-running models

COMPUTATIONAL DOMAIN

We employ a simplified description of the ESSs that eliminates manufacturer specifications but produces the relevant and expected flow features. An overview is shown on the right.

- Inflow and outflow are open boundary conditions
- Walls are isothermal, no-slip walls
- Six modules are stacked vertically
- A single module is heated above ambient temperature
- Rectangular geometry:
  - 5 cm, 10 cm, and 20 cm inflow/outflow width
  - 80 cm module width
  - 2 cm or 4 cm gap height
  - 10 cm module height
  - 40 cm rack and module depth



*Not drawn to scale

NUMERICAL SIMULATIONS

Numerical Approach

Modeling the heat transport via convection can be challenging because the combination of design requirements, buoyancy, and turbulence creates:

- A large disparity between largest and smallest physical scales;
- Transitional flow, challenging classic subgrid-scale models;
- A large parameter space to explore.

Our approach is to perform finely-resolved numerical simulations:

- Second-order finite element control volume approach using in-house code Sierra/Fuego
- Highly-resolved numerical grid with approximately 20M elements
- No subgrid-scale modeling

We consider several different parameters:

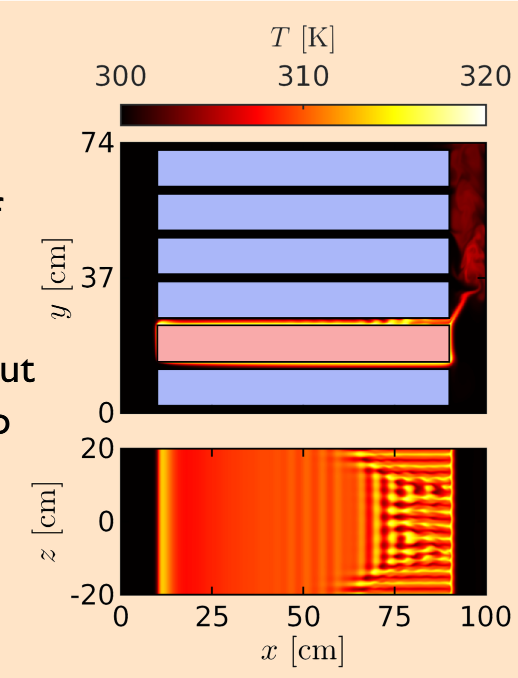
- Hot module temperature: 305 K, 310 K, 320 K, 340 K, 360 K
- Hot module location: Module 1, 2, 3, 4, 5, and 6
- Vertical spacing between modules: 2 cm, 4 cm
- Horizontal space in plenum: 5 cm, 10 cm, 20 cm

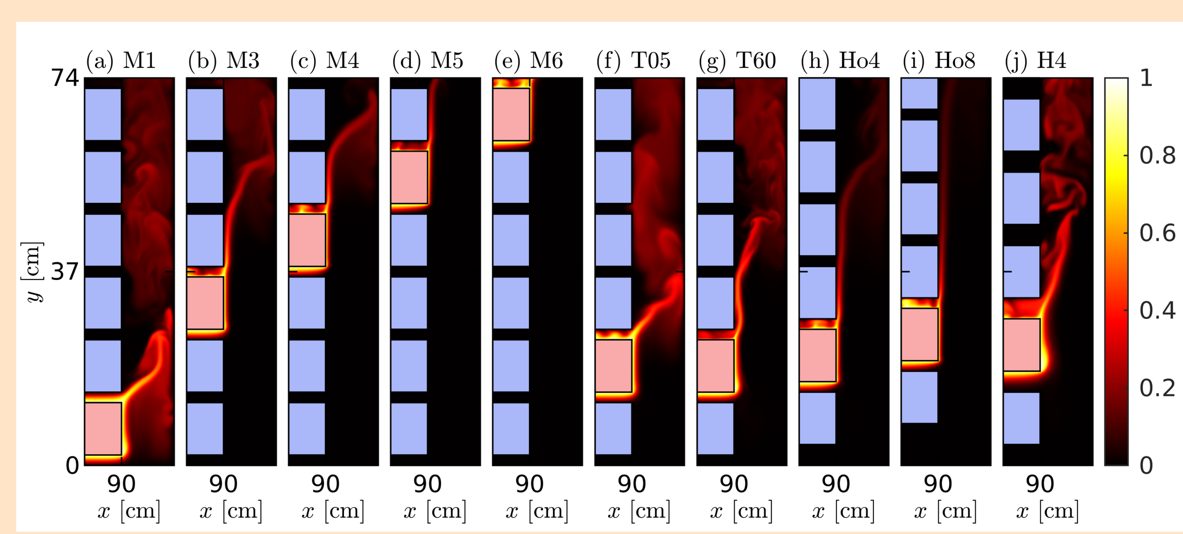
Approximate computational cost per simulation: 40-70k CPU hours.

Statistics are collected after flow becomes statistically stationary, approximately 20-40 seconds after initialization.

Flow Visualization

On the right are instantaneous temperature snapshots at the center plane ($z = 0$ cm) and at the center of Gap 3 ($y = -12$ cm) for a simulation with Module 2 heated to 320 K. Air moves from left to right, and up and out of the domain due to buoyancy. In Gap 3, an unstable Rayleigh-Bénard-Poiseuille instability forms increasing the heat transfer to Module 3 compared to Module 1. Additional simulations are shown below.

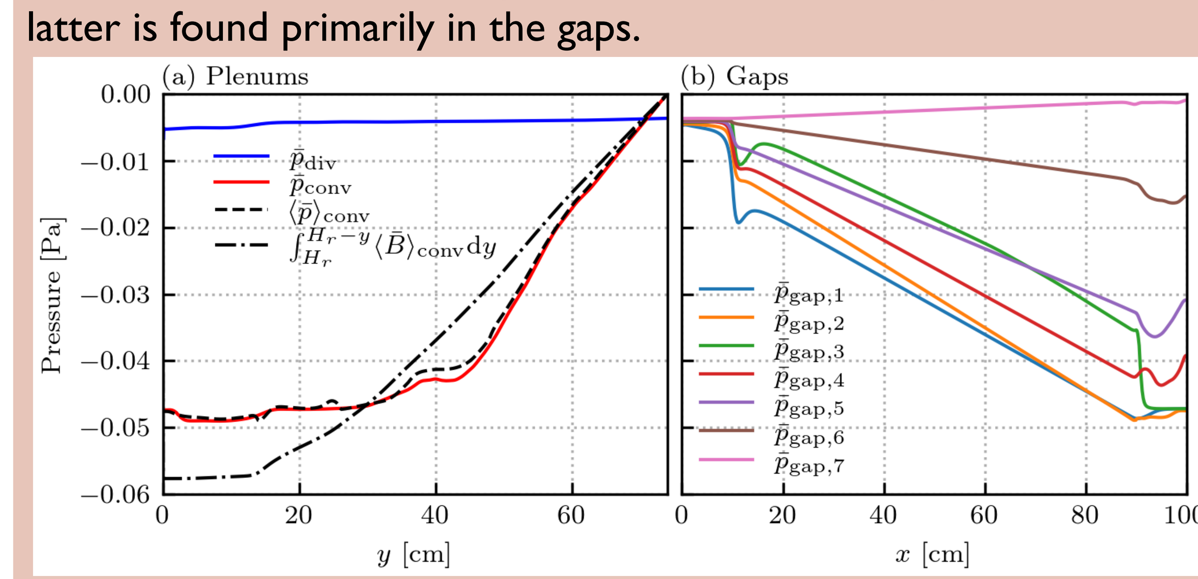




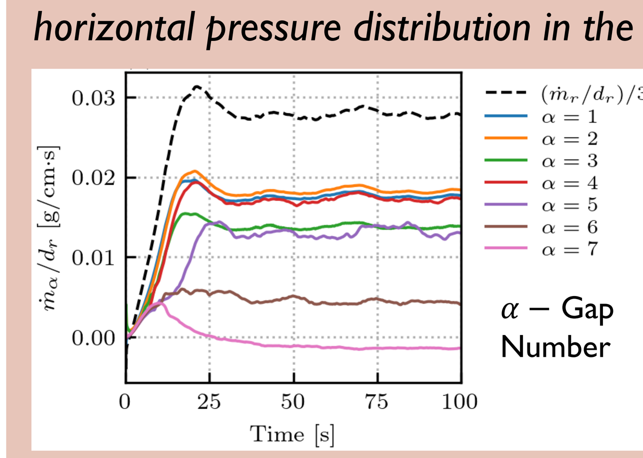
Instantaneous snapshots of the normalized temperature difference in the converging plenum from 10 different simulations.

Pressure Effects

Pressure changes are primarily driven by two effects in this rack: buoyancy and viscous drag. The former is found primarily in the vertical channels when temperature differences are present, and the latter is found primarily in the gaps.



Vertical pressure distributions through the plenums (left) and horizontal pressure distribution in the gaps (right).



A consequences of buoyancy and drag is an asymmetric distribution of air flow through the modules.

Mass flow rates through each gap and through the rack.

INTEGRAL-SCALE ANALYSIS

The transport equation for the mean temperature difference is

$$\frac{\partial}{\partial x}\left(\overline{u_i \Delta T}\right) = \frac{\partial}{\partial x_i}\left(\alpha \frac{\partial}{\partial x}\left(\Delta \bar{T}\right)\right).$$

Consider control volumes in the converging plenum that are edge aligned; two example control volumes are shown below in green and magenta dashed lines. Source terms for changes in $\langle \overline{u_i \Delta T} \rangle$, where $\langle \cdot \rangle$ indicates a plane average, are

$$\left\langle \overline{u_y \Delta T} \right\rangle_t - \left\langle \overline{u_y \Delta T} \right\rangle_b = \hat{S}_{mod} + \hat{S}_{gap} + \hat{S}_{rack}.$$

We derive the source terms for the change in $\langle \Delta \bar{T} \rangle$ to isolate buoyancy effects,

$$\langle \Delta \bar{T} \rangle_t - \langle \Delta \bar{T} \rangle_b = S_{mod} + S_{conv} + S_{rack} - S_{var} - S_{turb}.$$

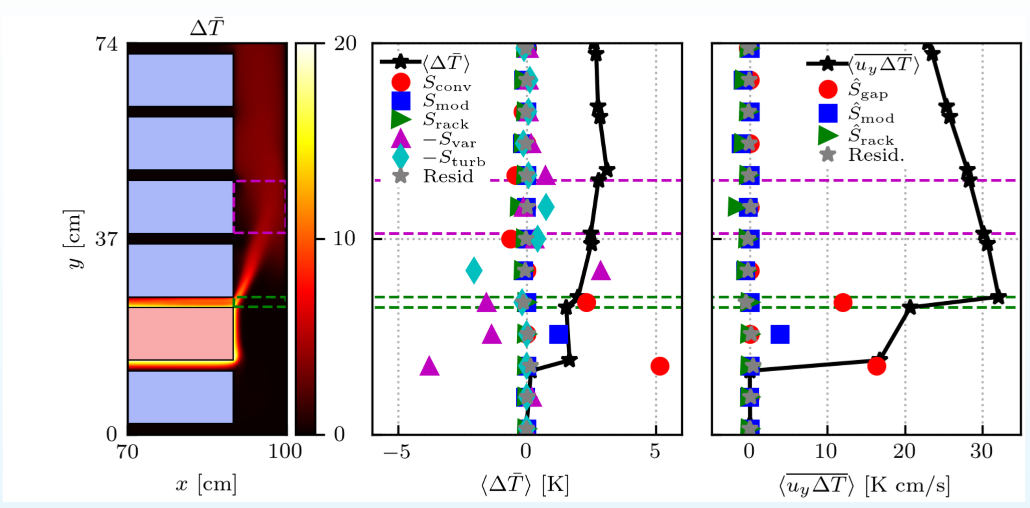
where,

$-S_{mod}$ and S_{rack}: temperature increase due to heat transfer with module and rack wall, respectively;

$-S_{conv}$ or S_{gap}: temperature increase due to convection;

$-S_{var}$: temperature increase due to spatial variability and temperature/velocity correlations across the plenum;

$-S_{turb}$: temperature increase due to turbulent fluctuations.



Time-averaged temperature differences (left) in converging plenum and source terms for $\langle \Delta \bar{T} \rangle$ (center) and $\langle \overline{u_i \Delta T} \rangle$ (right).

APPROXIMATE ALGEBRAIC MODELING

Model Overview

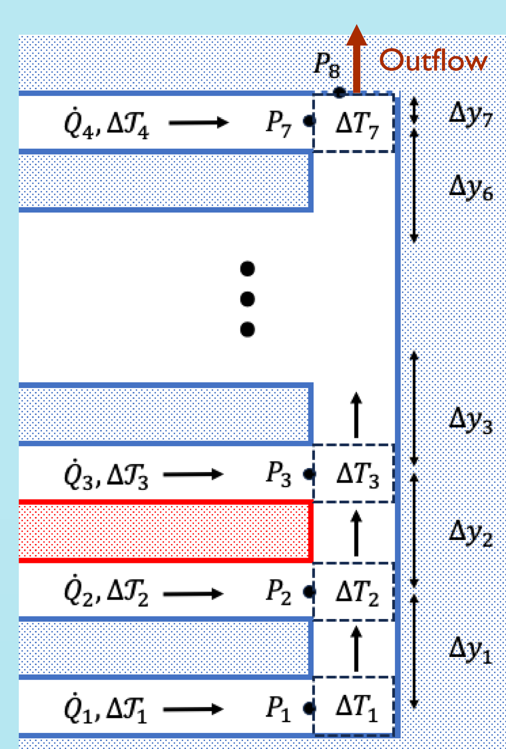


Illustration of approach to deriving fast-running entrainment models

The integral-scale analysis provides useful information to make the necessary assumptions to derive an algebraic network model, shown below as

$$p_{\alpha+1} - p_\alpha = \rho_\infty g \frac{\Delta T_\alpha}{T_\infty} \Delta y_\alpha,$$

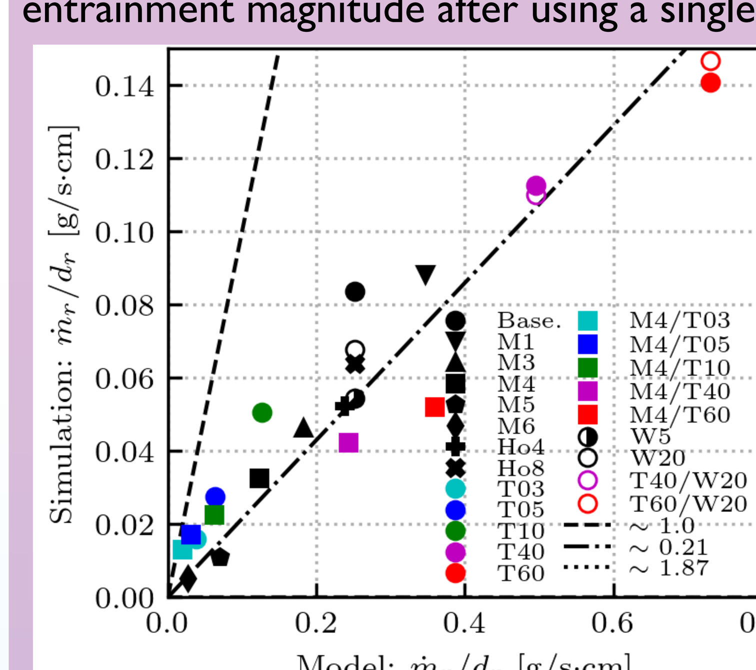
$$\Delta T_\alpha = \sum_{i=1}^{\alpha} Q_i \Delta T \Big/ \sum_{i=1}^{\alpha} Q_i,$$

$$\frac{Q_\alpha}{d_m} = -\frac{p_\alpha h_{gap}^3}{12 \mu_\infty w_m}.$$

Solution of the implicit equations can be determined quickly, $\mathcal{O}(< 10^{-3})$ CPU hours.

Comparison to Simulations

Direct comparisons are made between the network model and numerical simulations. Despite the network model requiring many orders of magnitude less computational work, it provides a good first-order approximations of air entrainment magnitude after using a single correction factor.



Parity plot showing correspondence between mass flow rate through the rack calculated from the simulation and from the network model.

SUMMARY

- Buoyancy drives air entrainment and airflow through battery modules based on vertical plume height.
- Integral-scale analysis identifies importance of mixing and inhomogeneity to create buoyancy in the converging plenum
- A steady algebraic model predicts air entrainment trends using a balance between buoyancy and drag

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