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Toward understanding the effect of venting within simplified energy storage systems

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BACKGROUND

Large-scale energy storage systems (ESSs) are becoming an integral part of maintaining a stable grid. Battery cells, however, are prone to degradation and inevitable failure, leading to thermal runaway and hot volatile gas being ejected through venting. Predicting when combustion will occur internally is critical for assessing the likelihood of module-to-module thermal runaway propagation and identifying fuel-rich conditions that could deflagrate if suddenly exposed to oxygen and/or an ignition source.

MODELING CHALLENGES

Modeling vent gas propagation and subsequent combustion is very challenging because of:

- The nonlinear coupling between turbulence, buoyancy, and chemical reactions;
- The geometrical complexity and disparity between largest and smallest scales;
- Transitional flow regimes, challenging classic subgrid-scale models;
- A vast parameter space not amenable to simple empirical correlations

OBJECTIVE

To examine the dependence of heat transfer, air entrainment, and vent gas propagation on vent failure characteristics in idealized rack-scale ESSs

APPROACH

Simplified 2D computational domain:

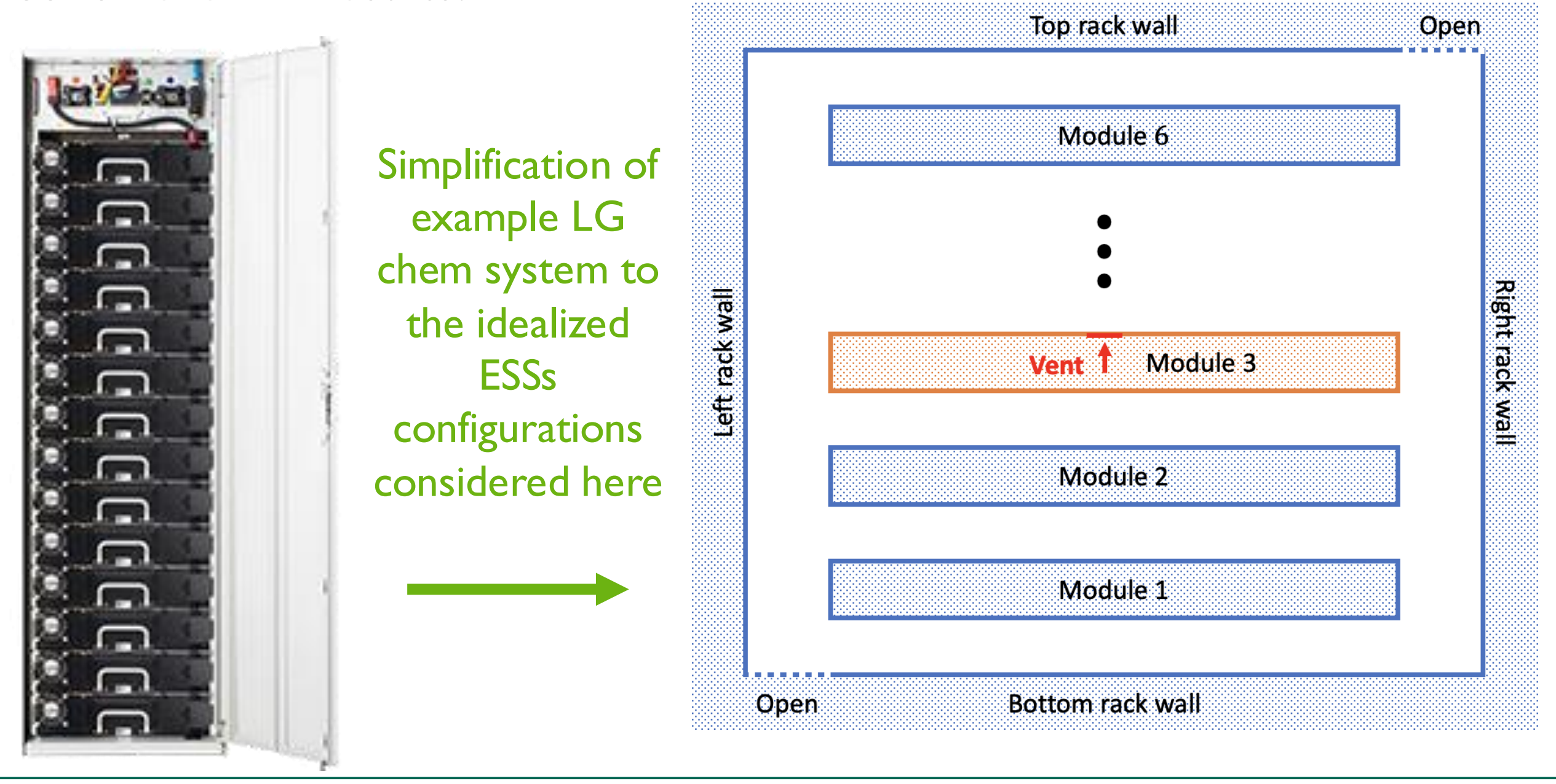
- Inflow and outflow are modeled as open boundary conditions
- Small slit on selected module represents vent port
- Remaining boundaries are modeled as isothermal, no-slip walls
- Six modules represented as rectangles are stacked vertically
- Steady vent inflow of H_2/CO/CO_2/CH_4 mixture
- Effects of vent velocity (colors), vent temperature (open/closed), and vent module (symbol) are considered in results.

Geometry (not to scale):

- 10 cm opening width
- 80 cm module width
- 2 cm gap height
- 10 cm module height
- 1 cm vent width

Numerical simulations:

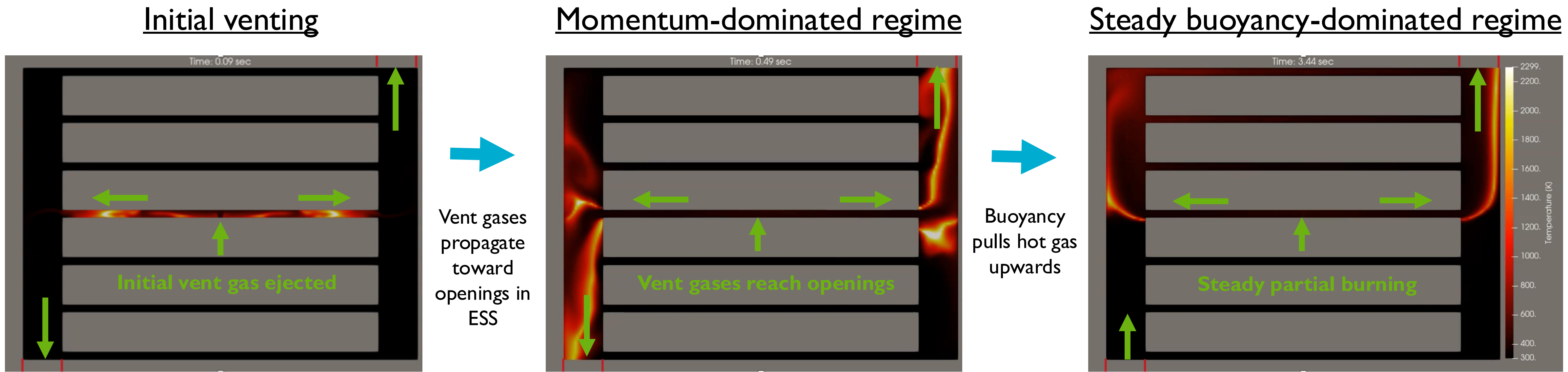
- Second-order finite element control volume approach (Sierra/Fuego)
- Reynolds-averaged Navier-Stokes (RANS) simulations using $k-\epsilon$ model
- Radiative transport using Thurgood quadrature type of 4th order


Simplification of example LG chem system to the idealized ESSs configurations considered here

TEMPORAL EVOLUTION

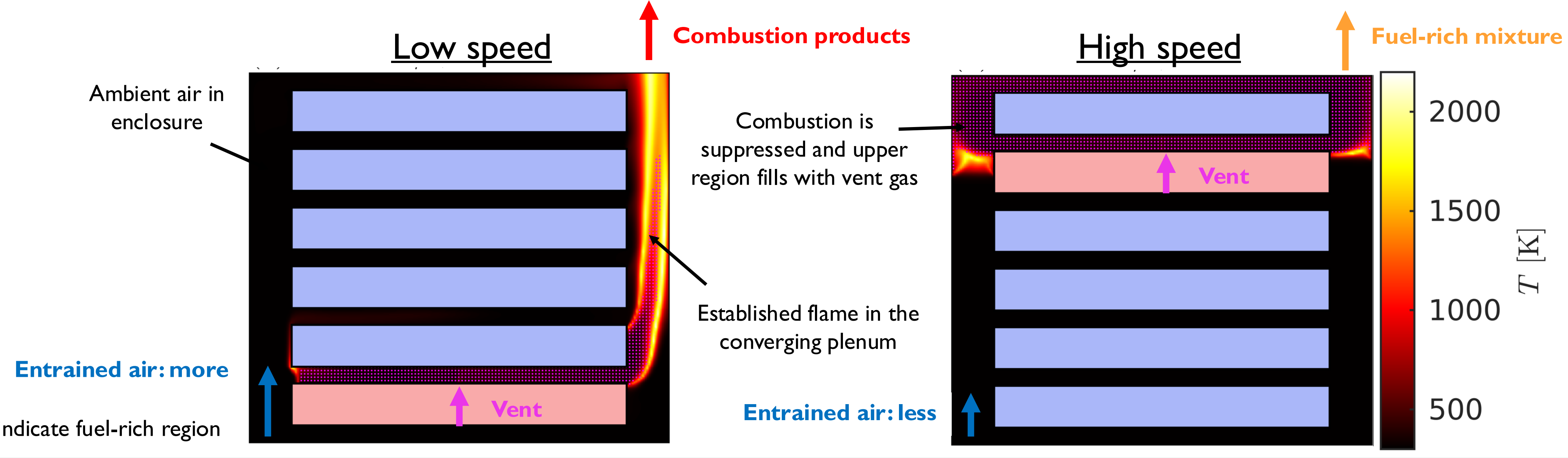
Vent gases are injected into the rack through a small gap between modules at a steady prescribed velocity. The gases are ignited and propagate toward the openings of the energy storage system as a mixture of vent gases, combustion products, and air. After 2-3 seconds, buoyancy pulls the hot gases upward, causing a switch from gas rejection to air entrainment through the bottom left opening, enabling some combustion within the ESS.

*indicates flow direction



FLOW REGIMES

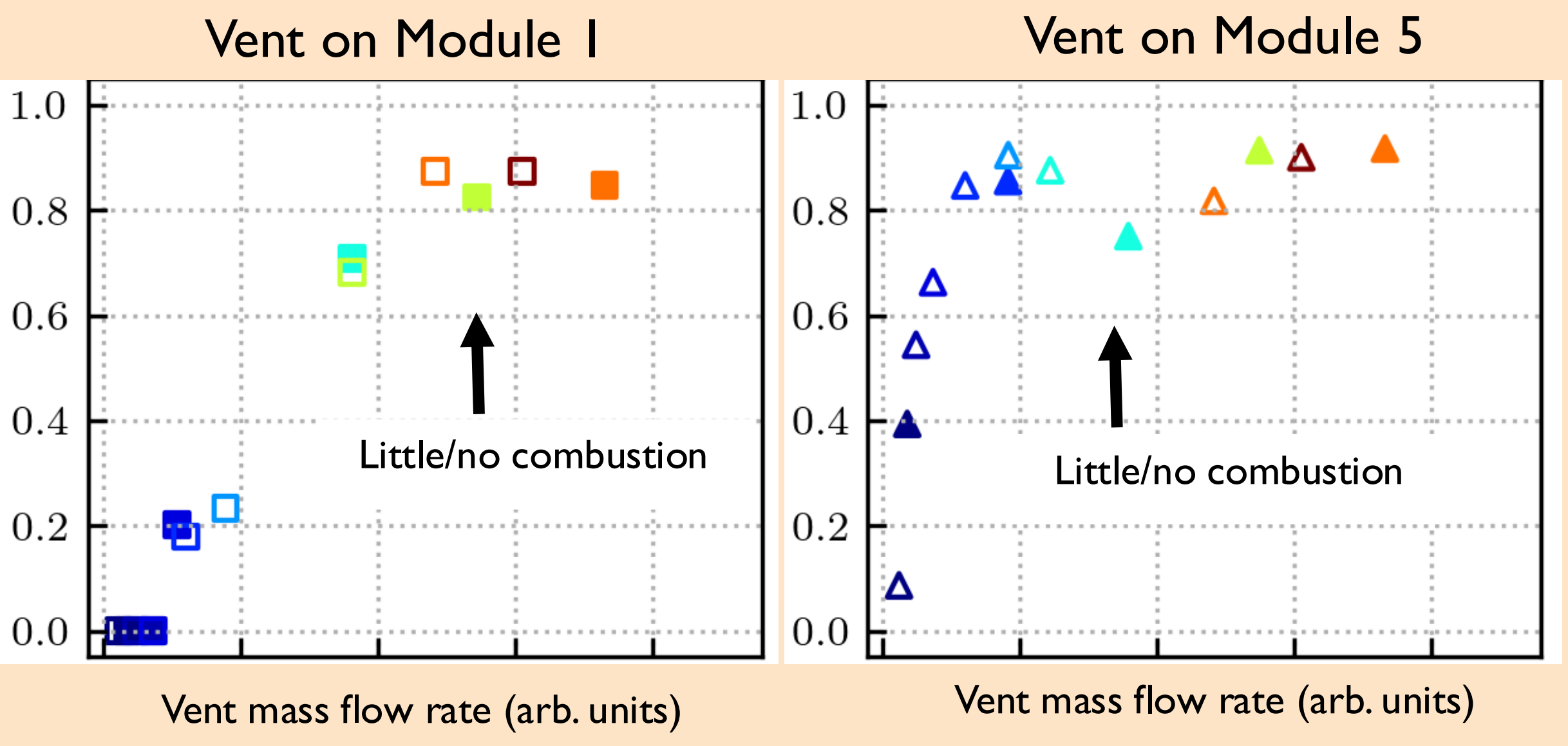
After 3-4 seconds, the flow reaches a statistically stationary state. This time scale is generally much shorter than the time over which venting occurs, providing some justification for the approximation. There is a strong sensitivity of the burning characteristics on vent velocity and vent module. Specifically, a lower vent module and/or decreased vent velocity leads to an increase in likelihood of sustained combustion inside the ESS because buoyancy increases and entrains more fresh air. Conversely, higher vent module and increased vent velocity may lead to flame suppression or incomplete combustion, producing fuel-rich mixtures inside the ESS and increasing the likelihood of an explosion hazard. See examples to the right.



*pink dots indicate fuel-rich region

RESULTS

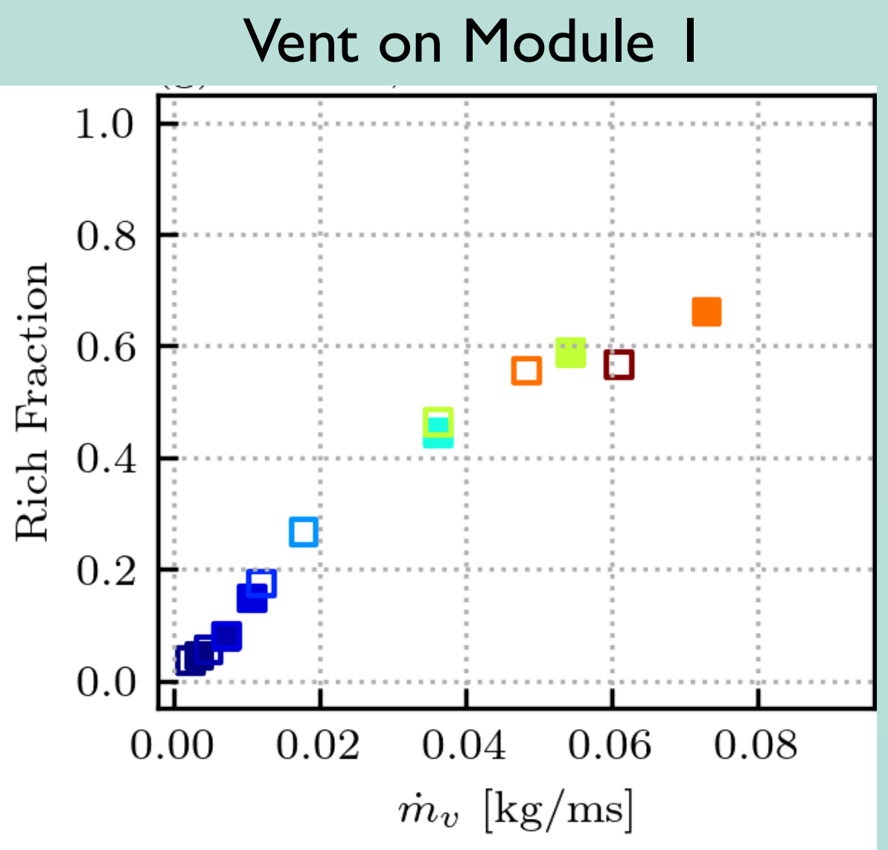
Fraction of vent gas that leave ESS uncombusted



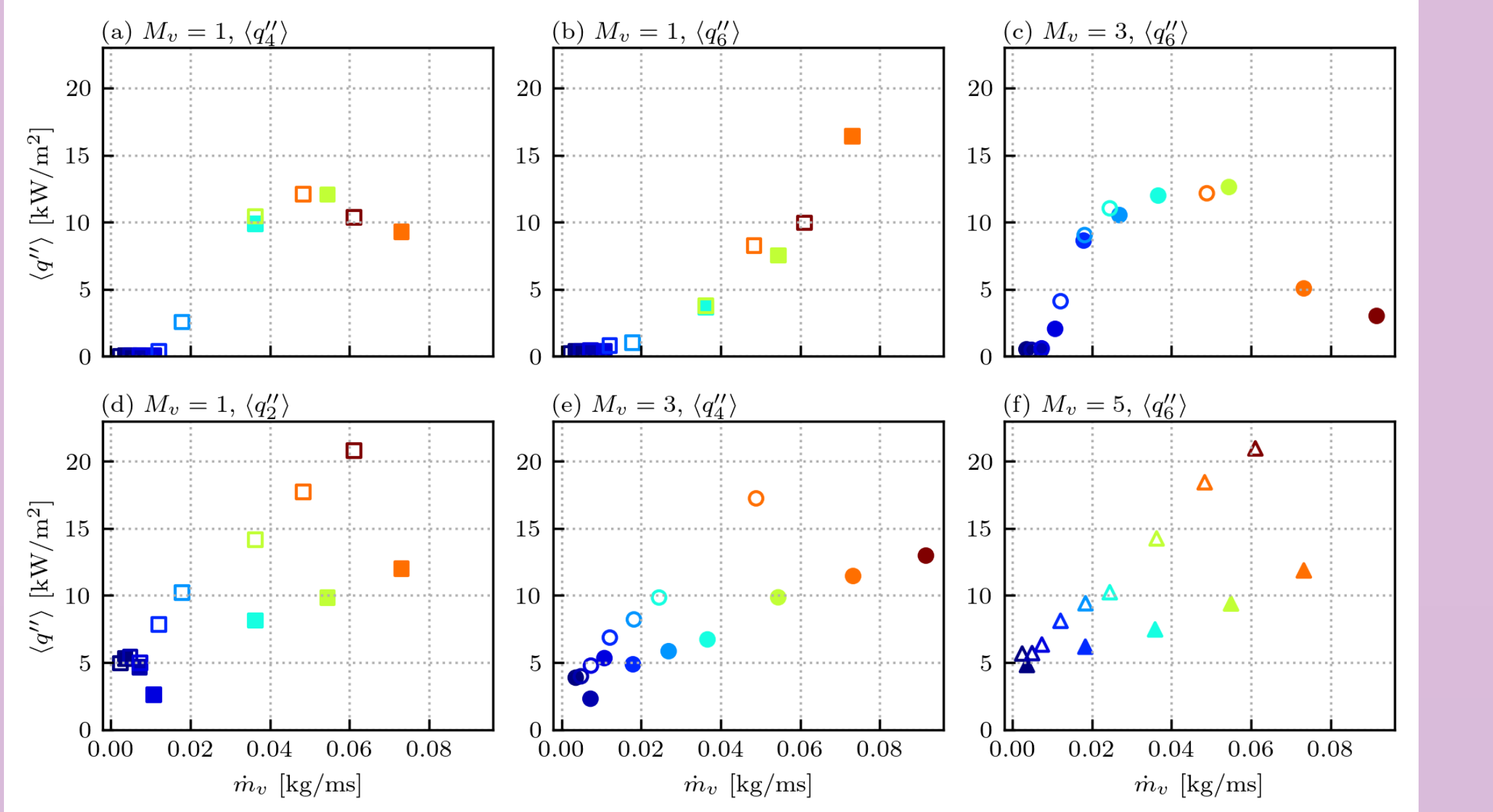
- When vent is close to bottom of the ESS and mass flow rate is small, all vent gas reacts within the ESS
- As mass flow rate increases, combustion is suppressed
- When the vent is positioned at the top of the ESS, combustion is suppressed at lower mass flow rates of the vent

Fraction of ESS where fuel/air mixture is rich

- As mass flow rate increases, the fuel rich region emanating from the vent propagates further into the ESS
- Buoyancy increases as ESS is filled and helps remove the vent gas before completely filling the ESS
- The general trends of rich fraction with respect to mass flow rate of the vent are insensitive to the position of the vent within the ESS (not shown here but available in provided reference)



Convective heat flux to surrounding modules



- Surface-averaged heat flux to non-adjacent module (module far from venting) shown in the top row peaks when flame impinges on the module and remains above zero after flame suppression
- Heat flux to adjacent module (module just above venting) shown in the bottom row scales with known jet impingement physics

**Symbols: square/circle/triangle – vent on Mod 1/3/5; color – vent velocity (blue – slow → red – fast); closed/open – vent temperature 800/1200K

SUMMARY

- This work examines the effect of vent velocity, temperature, and position using 2D RANS
- At small vent velocities and lower vent positions, buoyancy increases entrainment, enabling combustion within the ESS. Otherwise, combustion is suppressed and rich pockets form.
- Flame impingement creates a heat flux peak to non-adjacent modules in the ESS

FUTURE WORK

- Examine three-dimensional effects by extruding the modules in the spanwise dimension and including space between the modules and the front/back of the rack
- Apply recently developed structure-preserving reduced-order modeling methods to a fast-running, machine-learned network module to explore a larger parameter space

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SAND No. **SAND2026-21935C**

- Please see the following article for more details about this work: Michael Meehan, Andrew Kurzawski, and John C. Hewson. "Examination of entrainment, combustibility, and heat transfer due to cell venting inside simplified battery energy storage enclosures." Fire Safety Journal (2026): 104725.
- Special thanks to Loraine Torres-Castro, Randy Shurtz, Yuliya Preger, and the rest of the energy storage team for thoughtful discussions and advice.

This material is based upon work supported by the U.S. Department of Energy, Office of Electricity (OE), Energy Storage Division.