Optical measurement of gas venting and droplet spray from 18650 format lithium ion battery vent mechanisms

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Lithium ion batteries may fail violently under abuse conditions

- Electrical, thermal, and mechanical abuse
- Exothermic decomposition leads to thermal runaway
- Gas generation increases pressure
- Battery vent cap is used to prevent case rupture
  - Still presents safety concerns
  - Transient, multiphase flow through a unique geometry
Vent cap experiments recreate venting flow in a controlled environment.

- Positive terminal
- Electrical connection
- Anode/cathode layers

18650 Cell

Scored burst disk:
- Intact:
- Open:

Perforated plate:
- Different geometries from various manufacturers
High speed schlieren can be used to describe multiphase venting

- Technique images index of refraction gradient
  - Density or species
- Visualize gas and liquid components of flow\(^1\)
- Determine the effects of liquid phase on flow field
- Measurement of liquid and gas jets:
  - Projection angle
  - Spreading angle
- Flow front tracking

1. Mier et. al., Overcharge and thermal destructive testing of lithium metal oxide and lithium metal phosphate batteries incorporating optical diagnostics, 2017.
Burst pressure test fixture with high speed schlieren imaging

Fixture:
• Vertical orientation
• Liquid against vent

Camera settings:
• 384 px by 584 px
• ~0.1 to 0.15 mm/px
Imaging burst with only gas

• Carbon dioxide increases visibility in schlieren and mimics the live batteries
  – Up to 53% of vented gas

• Four individual jets from openings in vent cap
  – Two jets overlap in center of field-of-view

• Weak shock at opening

• Elapsed time: 13 ms

• Frame rate: 48 kHz

2. Golubkov et al., Thermal-runaway experiments on consumer li-ion batteries with metal-oxide and olivin-type cathodes. 2014.
1 mL of low viscosity, 26% sucrose solution added to simulate electrolyte

- Simulates ethylene carbonate:
  - Viscosity$^3$: 2.57 cP
  - Density$^4$: 1.11 g/mL
- Atomized flow and individual particles are not resolved
- Droplets follow gas flow
- Weak bottom jet
  - Burst disk attached
- Initial venting is almost entirely liquid
- Video: 48 kHz, 13 ms

Increasing viscosity demonstrates a different flow regime

- 1 mL of 69% sucrose
- More viscous, but with same density as electrolyte:
  - Viscosity\(^3\): 329 cP
  - Density\(^4\): 1.34 g/mL
- Particles are clearly visible, stretch, and some split outside the vent cap
  - Second wind blown regime as described by Reitz\(^5\)
- Droplet spray angle is initially wider than gas jet

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Electrolyte spray has uniquely distinct safety considerations within venting flow

Comparing droplet spray to gas:
- More chemical potential energy
- More initial momentum and retains momentum longer
- Coating nearby surfaces

Distinguishing between liquid and gas in schlieren images:
1. Record gas venting images
2. Mean image (480 frames)
3. Subtracted mean image from test images
4. Pixels much darker than mean image are droplets/spray
Making streak images to describe flow characteristics

Columns from successive images are arranged in frame order.

Perpendicular streaks a number of characteristic lengths \( L_C \) from vent:

\[
L_C = \sqrt{\frac{\bar{A}_{\text{opening}}}{\# \text{openings}}} = \sqrt{\frac{8.967 \text{ mm}^2}{4}} = 1.497 \text{ mm}
\]
Comparing streak images perpendicular to the flow at $10L_c$

- Gas venting is consistent between trials
- By visual inspection, flow is:
  - Projected outward at 21° from the battery axis
  - Gas jets in cones with ~12° half angle, as expected
- Outer edge of initial droplet spray is wider than gas jet
  - Spray angle approaches zero as liquid is expelled
- Low viscosity droplet cloud occupied more of the flow field for longer

6. Tollmien, Calculation of Turbulent Expansion Processes, NACA TM 1085
Droplet spray angle versus time at $10L_c$

Atomized, low viscosity jet is wider than high viscosity wind-blown spray.

Almost identical time durations.
Flow front tracking with axial streak images

- Flow front velocity decreases with addition of liquid and increased viscosity.
- Atomized, low viscosity flow initially matches gas front.
Time of flow arrival can be determined throughout the field of view.

**Low viscosity:**

**High viscosity:**
Particle image velocimetry (PIV) allows full field velocity measurement

- Olive oil droplets follow gas flow
- Pulsed laser sheet illumination
- Images recorded in pairs with a short time delay (10µs here)
- Image correlation determines displacement between images
Test apparatus constructed for steady state PIV measurement of gas venting
Test apparatus constructed for steady state PIV measurement of gas venting
Mean horizontal and vertical velocity components
Mean velocity magnitude measurement

- Same flow structures seen in schlieren images
- Dominated by horizontal (streamwise) velocity
- Core velocity ~Mach 1
- Laser sheet thickness captured portion of top jet
- Inaccurate velocities adjacent to vent cap
  - Highest velocity
  - Deformation of particle groups
Optical measurement techniques were used to quantify simulated battery venting

- High speed schlieren imaging of vent cap bursts
  - Jets are projected outwards at ~21°
  - Liquid spray angle begins large and approaches zero
  - Low viscosity sucrose solution venting is atomized as is typically seen with battery venting
  - Liquid decreases flow front velocity

- Preliminary steady-state PIV images allowed measurement of venting flow velocity field

- Next steps include:
  - Evaluating velocity profile under various conditions
  - Determining the interaction between the multiple jets
  - Describe the effects of the liquid phase in venting
Questions?

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Similar streak image trends between $2L_c$, $8L_c$, and $10L_c$
Horizontal (U) and vertical (V) velocity components recorded over 100 image pairs.

Little similarity between two sets of frame pairs.

Image pairs recorded at 15 Hz.

Frame pair 1
Frame pair 2
Frame pair 100
Vent cap experiments measured parameters which regulate the fluid flow.

**Burst Pressure:**
- **Pressure Transducer**
- **Ball Valve**
- **Vent Cap Holder**

<table>
<thead>
<tr>
<th>MTI Brand</th>
<th>$\mu$</th>
<th>$\sigma$</th>
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</thead>
<tbody>
<tr>
<td>Burst Pressure</td>
<td>2.158 MPa</td>
<td>0.081 MPa</td>
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<tr>
<td>Opening Area</td>
<td>8.967 mm$^2$</td>
<td>0.379 mm$^2$</td>
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<tr>
<td>Discharge Coefficient</td>
<td>0.850</td>
<td>0.024</td>
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**Area/Discharge Coefficient:**
- **Stagnation Pressure and Temperature**
- **Static Pressure**
- **Battery vent cap holder**
- **Outlet Valve**