Improving Battery Thermal Management Design using Six Sigma Process

by

Andreas Vlahinos, Kenneth Kelly, John Rugh & Ahmad Pesaran

National Renewable Energy Lab
Golden, CO
Outline

• Project Objectives & Approach
• Background Robust Design Techniques
• Prismatic NiMH Battery Thermal Analysis
  – Steady State Variation
  – Transient
• Summary and Future Plans
Objective and Approach

• The overall objective is apply variation analysis and Six Sigma design process to HEV battery thermal analysis
  – Better thermal performance
  – Longer battery life

• Approach:
  – Evaluate thermal management effectiveness of cylindrical and prismatic batteries with air or liquid cooling for HEV or Fuel Cell vehicles using FreedomCAR 40 kW power profile
  – Perform variation analysis and six sigma
Geometry and Load Cases

Two Battery Geometries:
  1. Prismatic
  2. Cylindrical

Two Coolants
  1. Air Cooled
  2. Liquid Cooled

Two Ambient Load Cases:
  1. Buffalo, NY (-20°C amb)
  2. Palm Springs (60°C amb)
Traditional Deterministic Design Approach

Accounts for uncertainties through the use of empirical Safety factors:

- Are derived based on past experience
- Do not guarantee safety or satisfactory performance
- Do not provide sufficient information to achieve optimal use of available resources
Six-sigma Design

- Identifying & qualifying causes of variation
- Centering performance on specification target
- Achieving Sigma level robustness on the key product performance characteristics with respect to the quantified variation
Robust Optimization

Histogram of Load Variation (Lognormal)

Thickness Variation (Normal) \(\mu_t=1.10 \text{ mm} \) \& \(\sigma_t=0.035 \text{ mm}\)

Thickness Variation (Normal) with \(\mu_t=0.88 \text{ mm} \) \& \(\sigma_t=0.0244 \text{ mm}\)

Desired Quality

Probabilistic Model

Noise Parameters \(\mu_p, \sigma_p\)

Sampling Method: Monte Carlo, LHS, CCD, BBM

Geometric FEM

Performance Function \(G\)

\(Q > Q_d\)

\(\mu_t, \sigma_t\)

Mean Value of Thickness \(\mu_t (\text{mm})\)

Mean Value of Performance \(\mu_G, \sigma_G (\text{MPa})\)

Histogram of Performance Function \(G\) for 0.85, 1.0 and 2.0 mm
Robust Optimization
reusable workflow template

Ford Motor Company
SAE – IEBEC 2001
Robust Optimization

reusable workflow template

Ford Motor Company

SAE – IEBEC 2002
Robust Optimization

reusable workflow template

Daimler Chrysler

SAE Powertrain Conference
Robust Optimization
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Plug Power
ASME / RIT Fuel Cell Conference
Robust Optimization

reusable workflow template

USABC / Ford
American Society of Quality
Reversible Process Template

Optimization Loop

Sampling Technique: LHS, CCM or D-Optimal
Regression analysis technique: Forward-stepwise-regression
Optimization Method: Sequential Unconstrained

Are $\sigma$ Quality Levels Acceptable?

PDS Loop

$\mu_{tga}$, $\sigma_{tgap}$
$\mu_R$, $\sigma_R$
$\mu_{Frate}$, $\sigma_{Frate}$

Sampling Technique: Box-Behnken Matrix design

Regression analysis technique: Forward-stepwise-regression

$\mu_{T_{max}}$, $\sigma_{T_{max}}$
$\mu_{dT}$
$\sigma_{dT}$

$\sigma$ Level for $T_{max}$ target
$\sigma$ Level for $dT$ target
$\sigma$ Level for $dP$ target

PDM

$T_{max}$
$R$
$F_{rate}$

dT

dP

Parametric Deterministic CAD/FEA Model

Optimization Method:
Sequential Unconstrained
Steady State Thermal Analysis with Input Parameter Variations
Inputs with Variation

- Gap Thickness
- Cell Resistance
- Flow Rate
- Six input parameters:
  1. $\mu_{tgap}$
  2. $\sigma_{tgap}$
  3. $\mu_R$
  4. $\sigma_R$
  5. $\mu_{Frate}$
  6. $\sigma_{Frate}$
Model Outputs

- max temperature
- differential temperature
- pressure drop

Six output parameters:
1. $\mu_{T_{\text{max}}}$
2. $\mu_{dT}$
3. $\mu_{dP}$
4. $\sigma_{T_{\text{max}}}$
5. $\sigma_{dT}$
6. $\sigma_{dP}$

Three Upper Specification Limits (USL)
Temperature Differential and Sigma Quality Levels
Design Space with $\sigma$ Quality Regions $T_{\text{max}}$
Design Space with $\sigma$-Quality Regions $dT$
Design Space with $\sigma$-Quality Regions $dP$
Design Space with \( \sigma \) Quality Regions All Parameters
Sigma Quality Levels Versus Mean Value

Sigma quality level versus $\mu_{\text{Air Gap Between Cells}}$

- Maximum Temperature Target
- Temperature Differential Target
- Pressure Drop Target

Air Flow Rate 1.05 scfm

Sigma Quality Level

$\mu_{\text{Air Gap Between Cells}}$ (mm)
Sensitivity Analysis

- The flow rate has the most impact on the maximum temperature.
- All three input design variables have about equal effect on the temperature differential.
- The internal battery resistance has no effect on the pressure drop.
Transient Thermal Response of Prismatic Batteries
FreedomCAR 40-kW Baseline Power Assist & Heat Generation Profiles

USABC FreedomCAR 40-kW Baseline Power Assist Profile

Heat Generation Profile for Prismatic Pack

BSF = 38
Inlet Temperatures for Air and Liquid Cooling

Inlet Temperatures versus time for Air and Liquid Cooling (Variable Temperature Case)

- **Air Cooldown**
- **Air Warmup**
- **Liquid Cooldown**
- **Liquid Warmup**

The graph shows the average inlet temperature in °C over time in seconds from the start of cooldown/warmup.

- The **Air Cooldown** line starts at a higher temperature and decreases sharply before leveling off.
- The **Air Warmup** line starts at a lower temperature and increases gradually.
- The **Liquid Cooldown** line starts at a higher temperature, decreases more gradually, and levels off.
- The **Liquid Warmup** line starts at a lower temperature, increases more gradually, and levels off.

The x-axis represents time from the start of cooldown/warmup in seconds, while the y-axis represents the average inlet temperature in °C.
Inlet, Outlet and Core Temperature for Palm Springs with High Air Flow Rate

Outlet Temperature versus Time for 40 kW FreedomCAR Power Profile Palm Springs Air High Flow

- Inlet Air Temperature
- Outlet Air Temperature
- Average Core Temperature

Time (sec)

Average Outlet Temperature (°C)
Core Temperature for Palm Springs with High Air Flow Rate

Core Temperature versus Time for 40 kW FreedomCAR Power Profile Palm Springs Air High Flow

Temperature (°C)

Time (sec)

Minimum Core Temperature
Average Core Temperature
Maximum Core Temperature
Minimum Steady State
Average Steady State
Maximum Steady State
Core Differential Temperature for Palm Springs with High Air Flow Rate
Average Core Temperature (Palm Springs)

Average Core Temperature versus Time for Palm Springs

Temperature (°C) vs. Time (sec)

- Palm Springs High Air Flow Rate
- Palm Springs Low Air Flow Rate
- Palm Springs High Liquid Flow Rate
- Palm Springs Low Liquid Flow Rate
Distribution of Maximum Core Temperature over time Palm Springs Air High Flow

Histogram Count (of 2700 sec) of Maximum Core Temperature

Temperature (°C)

34 36 38 40 42 44 46 48 50 52 54

Distribution of Max Core Temperature
Average Core Temperature (Buffalo)

Average Core Temperature versus Time for Buffalo

- Buffalo High Air Flow Rate
- Buffalo Low Air Flow Rate
- Buffalo High Liquid Flow Rate
- Buffalo Low Liquid Flow Rate
Summary

• Demonstrated a re-usable process for including statistical variation of input parameters for battery thermal analysis
  
• Initial analysis with variation shows:
  – $T_{\text{max}}$ is most difficult criterion to achieve with the given design constraints and assumptions
  – Effect of conflicting design constraints on sigma quality level

• Completed first round of transient thermal analyses on prismatic design

• Initial transient results show
  – the importance of including transient analysis
  – liquid cooling is more effective, but pressure drop higher
  – transient cooling and warm up time of the heat transfer fluid needs to be considered.
Future plans

1. Introduce feedback control on the fan
   1. Fan on–off, speed levels, etc
   2. Evaluate the effectiveness of various control systems on thermal performance.
2. Find the effect of power pulses in the load cycle on thermal transient.
3. Obtain a non-uniform heat generation profile from published information or other test data (thermal imaging).
4. Modify duty-cycle to include appropriate diurnal ambient and load conditions
5. Perform transient thermal analysis on cylindrical battery pack
Acknowledgments

This research effort was funded by the Department of Energy (DOE), Office of the FreedomCAR and Vehicle Technology.

The authors would like to express their appreciation to:

- **Robert Kost**, team leader of the FreedomCAR and Vehicle Technology office
- **Tien Duong**, Technology Manager of Electrochemical Energy Storage program and
- **Ted J. Miller** of Ford Motor Company and FreedomCAR Battery Tech Team Chairman
- **Bruce Bryant**, of Ford Motor Company