Validation Results of Pressure Independent First-Order Thermal Models of High-Altitude Balloon Gondolas

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Introduction

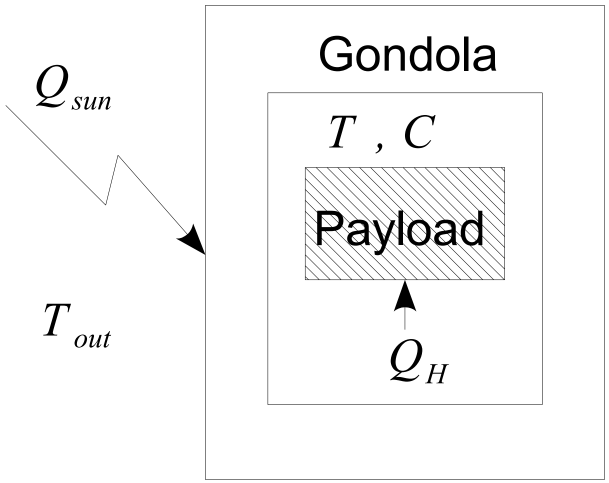
- How can we quickly evaluate whether or not equipment within a high-altitude gondola will stay within an acceptable temperature range during a short-duration flight?
- Short-duration $\leftarrow$ No steady state
  - Temperature constantly changes on ascent and descent
  - Temperature dynamics are slow to respond
- Need a dynamical thermal model

Introduction

- Approach:
  - Identify a first-order thermal model for an assumed isothermal node (the payload).
    - Desirable for the I.D. procedure to be easily carried out in an academic laboratory at ground level atmospheric pressure.
- Raises questions:
  - Will a suitable model depend on atmospheric pressure?
    - If so, by how much?
    - Is pressure independence acceptable?

Model Identification

- Assume a single isothermal node:



- Energy balance:

$$C\dot{T}(t) = -\frac{1}{R}\left(T(t) - T_{out}(t)\right) + Q_H(t) + Q_{sun}(t)$$

Model Identification

- Experiment:
  - Zero Q_{sun} and apply a known Q_H
    - T_{out} should be constant (if not, average it)
  - Record:
    - Time, Payload Temperature T, and T_{out}
- Notice the analytical solution to the differential equation is:

$$T(t) = (T(0) - a_2) e^{\frac{-t}{a_1}} + a_2$$

where $a_1 = RC$ and $a_2 = T(\infty)$

Model Identification

- Find a_1 and a_2 that make the analytical solution best-fit the recorded data.
- How? Minimize $\|\underline{e}\|^2$ where:

$$\underline{e} = \begin{bmatrix} T_{meas}(t_1) - \left((T_{meas}(0) - a_2) e^{\frac{-t_1}{a_1}} + a_2 \right) \\ T_{meas}(t_2) - \left((T_{meas}(0) - a_2) e^{\frac{-t_2}{a_1}} + a_2 \right) \\ \vdots \\ T_{meas}(t_n) - \left((T_{meas}(0) - a_2) e^{\frac{-t_n}{a_1}} + a_2 \right) \end{bmatrix}$$

Lots of ways to solve this!

- MATLAB ← “lsqnonlin” works well

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Model Identification

- Solving the minimization problem provides:
  - Time-constant: $a_1 = RC$
  - Steady-state temperature: $a_2 = T(\infty)$
    - Notice: we don't have to collect data until steady-state is reached!
- To find thermal resistance:
  - Use steady state solution: $0 = -\frac{1}{R}\left(T(\infty) - \hat{T}_{out}\right) + Q_H$

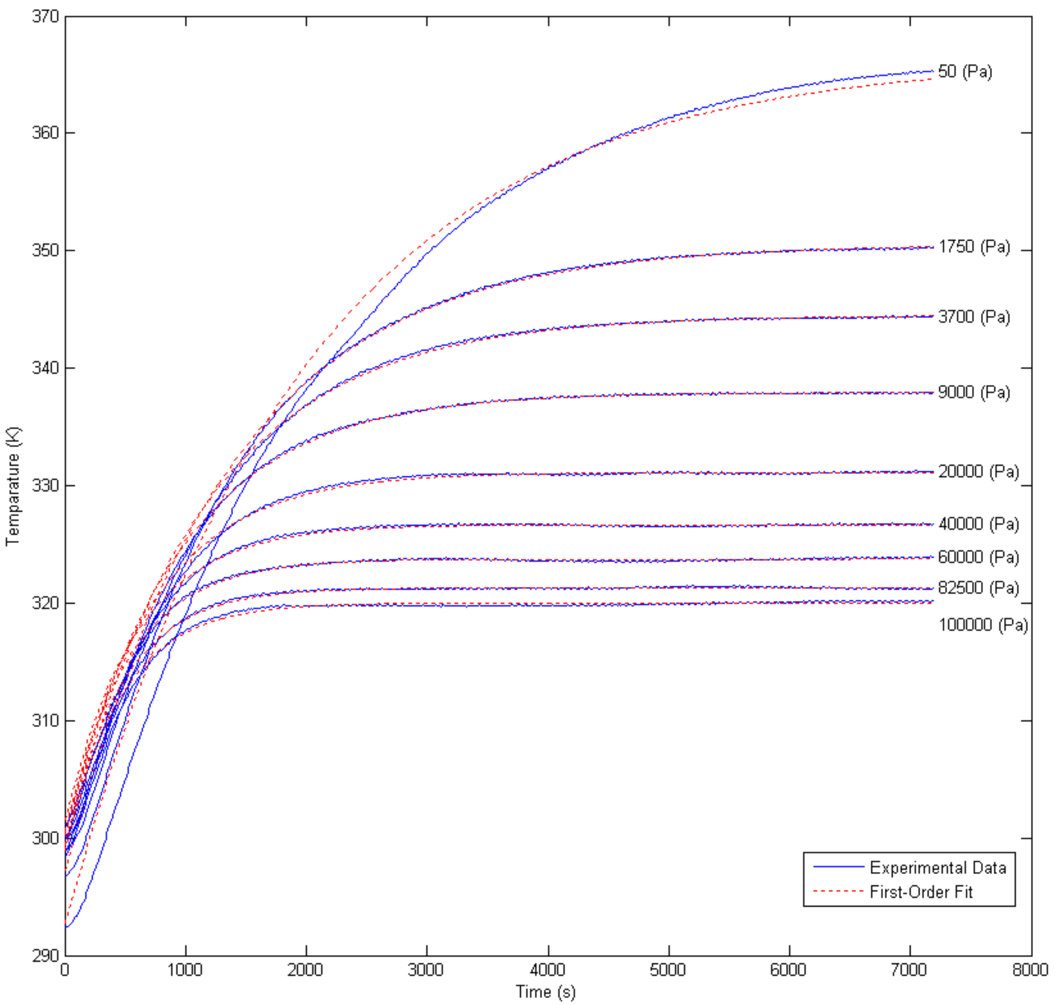
  so, $R = \frac{T(\infty) - \hat{T}_{out}}{Q_H}$
- Thermal capacitance: $C = \frac{a_1}{R}$

Model Identification

- To find Q_{sun}:
  - Zero Q_H
  - Place gondola in direct sunlight
  - Allow payload to reach a steady-state temperature
    - Could also curve fit.
- Then, $$Q_{sun} = \frac{T_{meas}(\infty) - \hat{T}_{out}}{R}$$

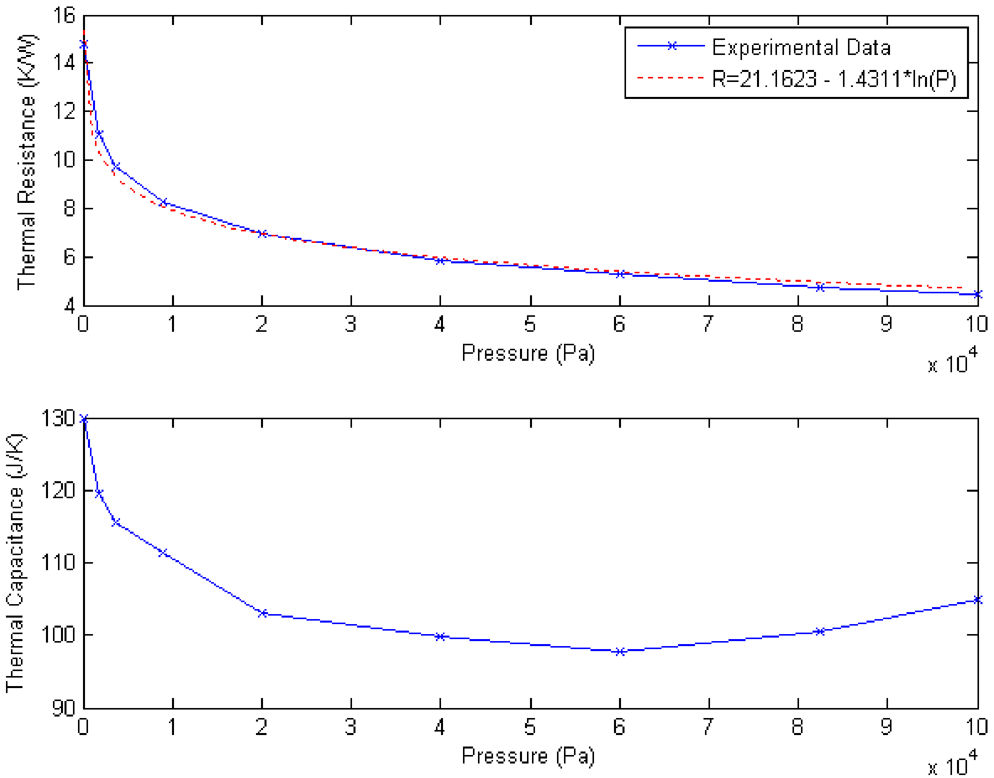
Laboratory Results

- In order to investigate pressure dependence, the first part of the I.D. procedure was carried out on a test gondola at different pressures in a vacuum chamber.



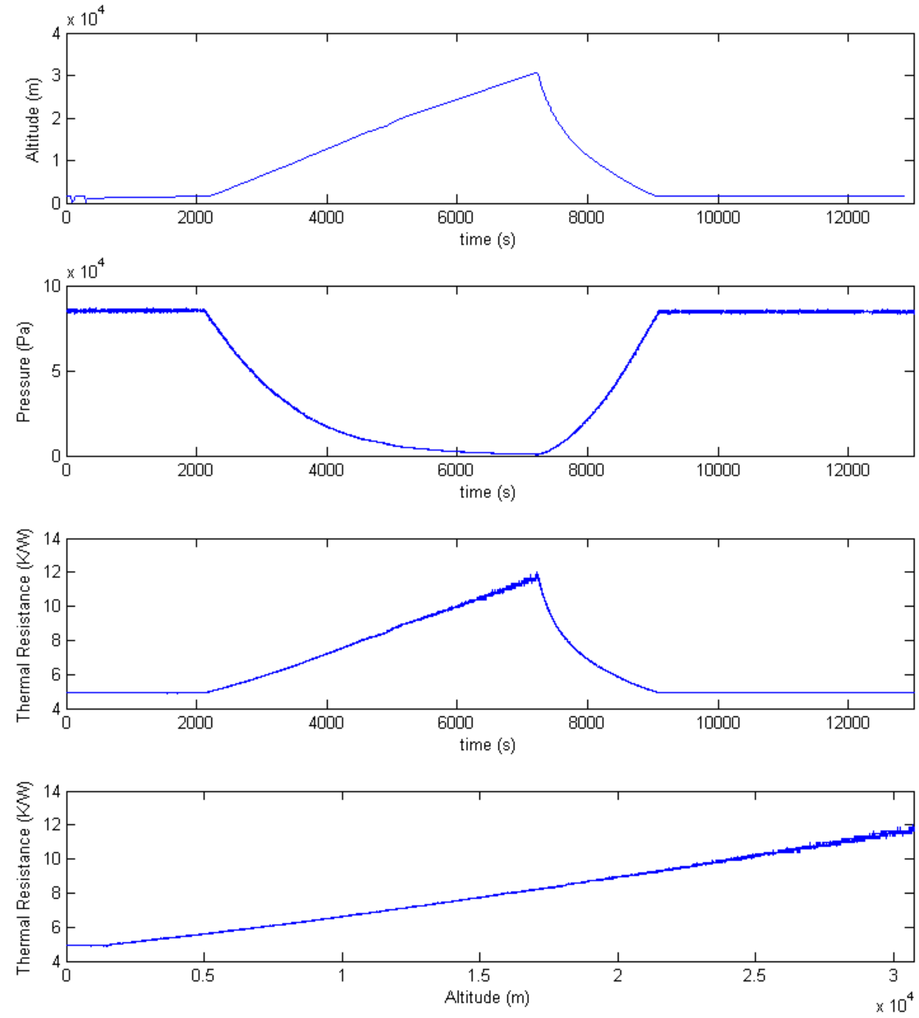
Laboratory Results

- Provided data on thermal resistance and thermal capacitance vs. pressure.
- Substantial change in thermal resistance.
  - Fits logarithmic curve!
- Minor change in thermal capacitance.



Laboratory Results

- Using the fitted thermal resistance curve and a typical flight altitude and pressure profile, we find:
  - it is almost affine with altitude.
  - at constant ascent, it is almost affine with time.



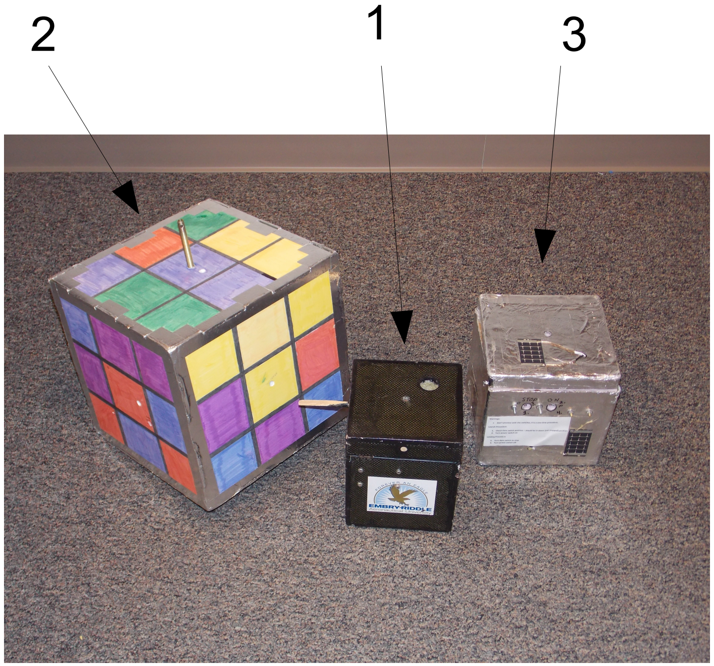
Laboratory Results

- Trends show that thermal resistance is pressure dependent
  - Thermal capacitance? ← not too conclusive
- Currently carrying out test on different gondolas to determine if thermal resistance vs. pressure is consistently in the form of a logarithmic curve.
  - If so, two-point calibration could be used for building a pressure dependent model (would require one test to be performed in a vacuum).

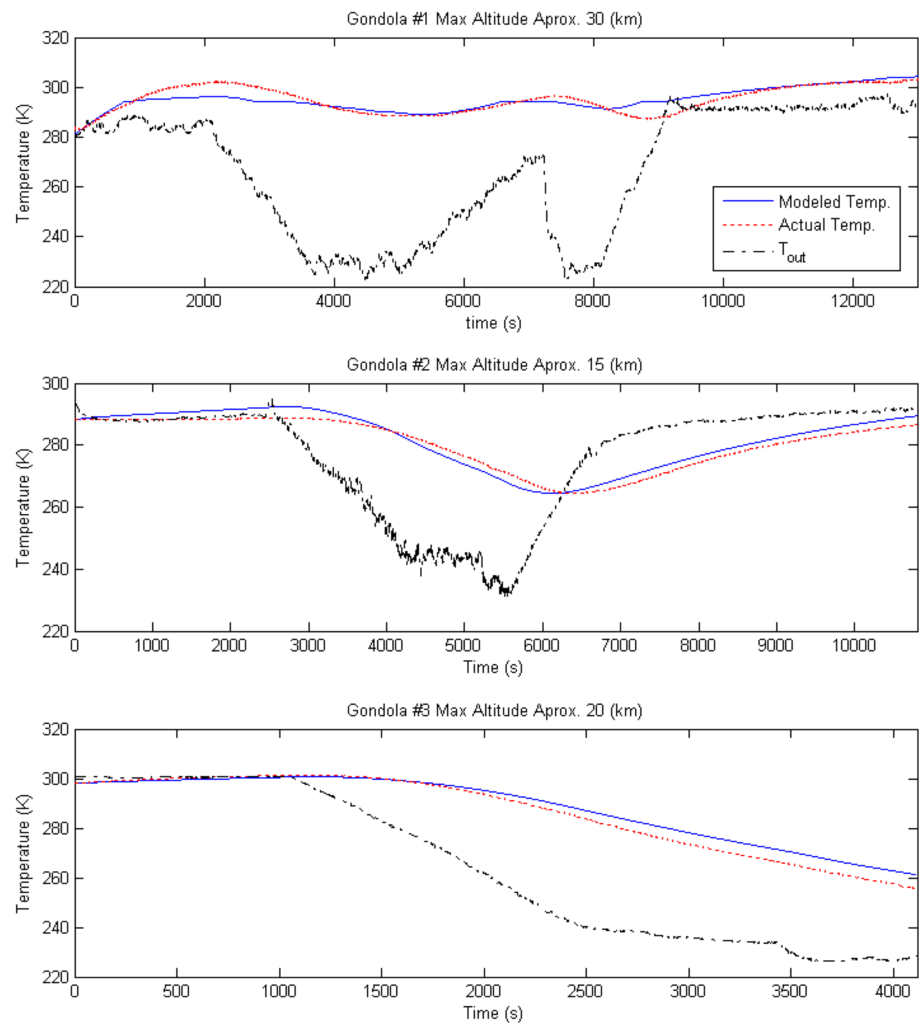
Validation

- Test the model's effectiveness by evaluating its response to data not used for identification.
  - How well does this response match the model response?
- Carried out validation process for three gondolas that flew on three different flights.
  - Gondola 1 → maximum altitude = 30 (km)
  - Gondola 2 → maximum altitude = 15 (km)
  - Gondola 3 → maximum altitude = 20 (km)

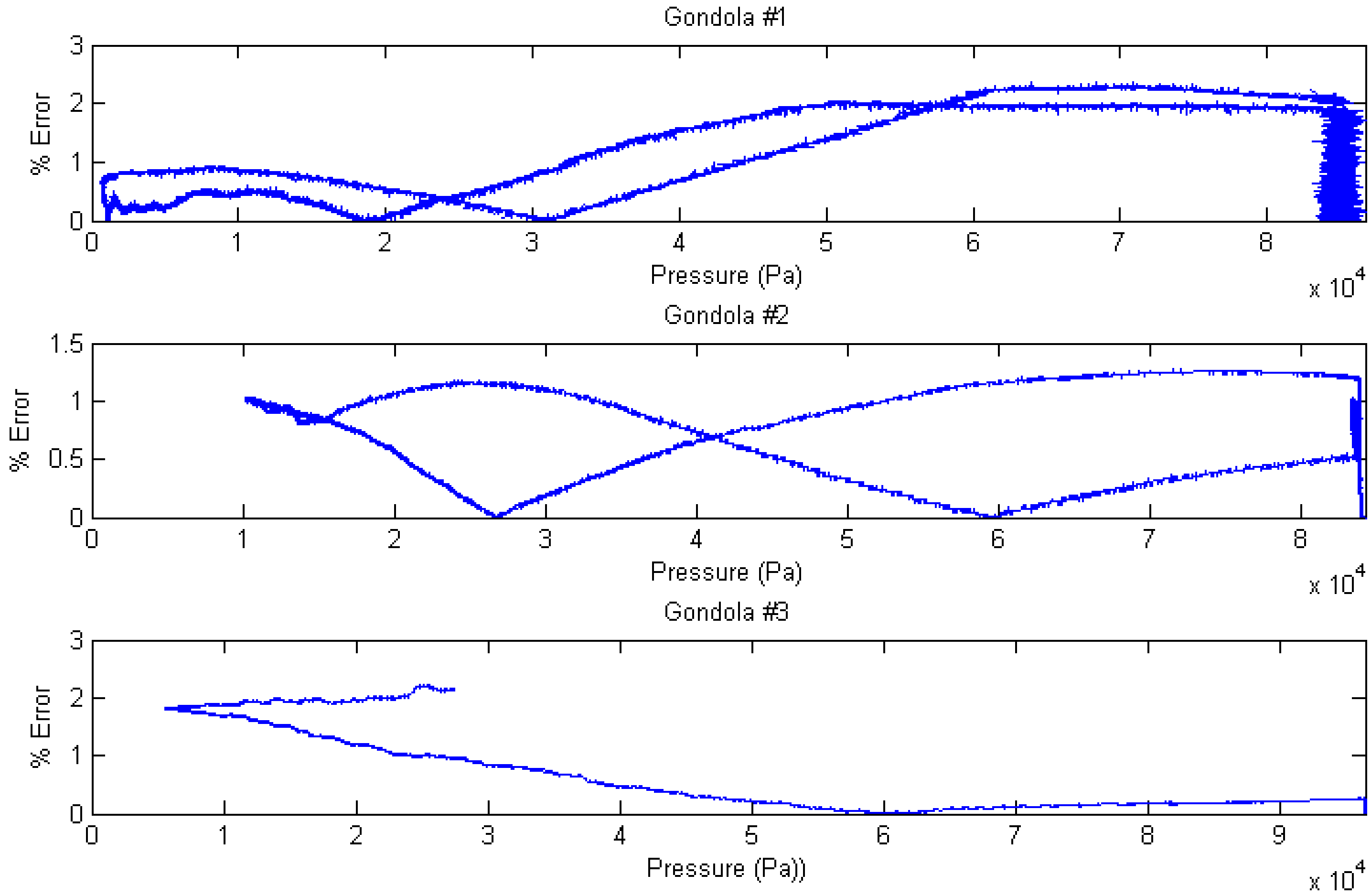
Validation



Gondola	Q_{sun} (W)	R (K/W)	C (J/K)
1	3.189	4.803	610.17
2	2.161	2.560	980.38
3	0.733	5.724	399.42



Validation


Gondola #1
% Error
Pressure (Pa)
x 10^4
Gondola #2
% Error
Pressure (Pa)
x 10^4
Gondola #3
% Error
Pressure (Pa))
x 10^4

Validation

- Less than three percent error (measure is somewhat misleading)
- No consistent lead/lag in the response.
  - May show up with more tests.
- Measured data is colder on ascent and descent than model response.
  - Unmodeled forced-air convective cooling?

Conclusion

- Pressure independent models seem to provide acceptable results for short duration flights even though thermal resistance appears to be highly pressure dependent.
- Future improvements:
  - The solar input test is highly dependent upon time of day and year.
    - Use National Renewable Energy Lab solar tables to scale value for time of day/year.
  - Provide correction factor for forced air convection (probably make this a function of pressure)
    - Would likely require an additional experiment.
  - Try 2-point calibration for developing pressure dependent model.