MATLAB, Simulink, and Cantera for Aerospace Thermodynamic System Modeling

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MATLAB, Simulink, and Cantera

MATLAB

```matlab
function u_out = compressor(u_in)
    global nsp data
    T_in = u_in(1);
P_in = u_in(2);
W_in = u_in(3);
X_in = u_in(4:nsp+3);
    set(data.compressor.out.gas,'T',T_in,'P',P_in,'X',X_in);
data.compressor.in.W = W_in;
    set(data.compressor.out.gas,'T',T_in,'P',P_in,'X',X_in);
data.compressor.out.W = data.compressor.in.W;
Ft_out = data.compressor.PR * pressure(data.compressor.in.
    Ht_in = enthalpy_mass(data.compressor.in.gas); %enthalpy
    S_in = entropy_mass(data.compressor.in.gas); %entropy
```

Cantera

Simulink

2nd stage compressor
Simulink
...and MATLAB again

- `fmincon`, `fminbnd`, `fsolve`
  - Overall optimizers and nonlinear equation solvers
  - Minimize system mass or ensure conservation equations

- `ga_tool`, `patternsearch`
  - Non-gradient optimizers, though not necessary for current UAV model

Also...

- `structures`
  - Minimize variable handling and clarifies code
  - *for example, `compressor.in.W` (or `.gas`, `.PR`, `.pwr`)*
Cantera
(www.cantera.org)

• Developed by David G. Goodwin, Professor of Mechanical Engineering and Applied Physics at California Institute of Technology

• Open source chemical reaction code
  – Written in C++
    • Compatible with MATLAB, Python, Fortran

• Capabilities
  – Thermodynamic and transport properties
  – Chemical equilibrium
  – Chemical kinetics
  – Electrochemistry
  – Pure substance equations of state
  – Others…
Cantera
Cantera

MATLAB

gas = GRI30;
set(gas,'T',300.0,'P',OneAtm,'X','CH4:1,O2:2,N2:7.52');
equilirate(gas,'HP');
disp(gas)

Python

from Cantera import *
gas = GRI30()
gas.set(T = 300.0, P = OneAtm, X = 'CH4:1,O2:2,N2:7.52')
gas.equilirate('HP')
print gas

C++

#include "Cantera.h"
#include "GRI30.h"
#include "equilibrium.h"

main() {
    GRI30 gas;
gas.setState_TPX(300.0, OneAtm, "CH4:1,O2:2,N2:7.52");
equilirate(gas, "HP");
cout << gas;
}
Objective

• Design a representative hybrid solid oxide fuel cell power system for high-altitude, long-endurance flight

• Understand the effect of major variables on the system
  – system level variables: altitude, power level, duration
  – component level variables: efficiencies, fuel cell resistivity

• Optimize system design
  – Current figure of merit: minimize mass
UAV power system
UAV power system specifications

• Baseline system
  – 21 km altitude (68,897 ft)
  – 50 kW net electrical power
  – $\eta_{ad} = 0.8$ for compressor stage, 0.85 for turbine stage
  – 2 stage radial turbomachinery designs
  – Planar solid-oxide fuel cell
    • 700°C inlet temperature, 1 atm inlet pressure
    • 100°C temperature increase across stack (air-cooled)
    • Maximum of 25 cells per stack, 25 cm$^2$ single cell active area

• Variations:
  – Altitude: 16 km
  – Power: 20 kW
  – Sensitivities on compressor and turbine $\eta_{ad}$, fuel cell ASR and stack design
Assumptions and Limitations

- design system

  - design point steady-state analysis

    - off-design steady-state analysis
      - transient/dynamic analysis
      - mission analysis (integrated with airframe model)
Past studies

Previous work (most undocumented)
Minimize fuel cell system mass

Our work
Minimize (fuel cell system + fuel system) mass
Qualitative (pre)analysis

for constant fuel cell power,

small fuel cell
high current density
low voltage
big fuel tank

big fuel cell
low current density
high voltage
small fuel tank

∴ there is a optimum system that minimizes mass/volume
Effect of mission duration

1 day mission

20 day mission
Another view of mission duration

(using optimum solutions from previous plots)

1 day mission

20 day mission
Sensitivity studies

![Graph showing system mass vs. SOFC cell voltage for different durations and ASR values]

- **1 day duration**
- **20 day duration**

- **ASR = 1.0 Ω–cm²**
- **ASR = 0.4 Ω–cm²**

- **SOFC cell voltage, V**
- **System mass, kg**

- **η_{adc} = 0.7**
- **η_{adc} = 0.8**
Conclusions

• Combination of MATLAB, Simulink, and Cantera
  – Flexible and customizable interface
    • Currently using similar approach for lunar oxygen production system analysis
  – Scalable analysis capability
    • Cantera offers much more than currently being used here
    • MATLAB/Simulink as well
      – other toolboxes
        » Statistics, SimPowerSystems
      – Also full capability of Simulink
        » Dynamic and transient modeling

• UAV fuel cell system is possible when analyzed at the correct system level
  – especially for this application (high altitude, long endurance)
More information on this work

• Results will be presented in more detail on June 19
  – ASME Fuel Cell Science, Engineering, and Technology Conference in Irvine, CA
    • Paper # FUELCELL2006-97095

• Also available as a NASA Technical Memorandum
  – NASA TM-2006-214328
  – (will be online soon at http://ntrs.nasa.gov)
Lunar O₂ production model
Recommendations

• There is a better way to integrate these codes *(though we haven’t found it yet)*
• Simulink can only pass numerical signals
  – Structures (with different data types) would help
  – Cantera objects (pointers?) would be even better
• More focus on Simulink as a steady-state tool
  – e.g. more flexibility and power with algebraic loop solver
    • Currently using MATLAB’s `fsolve` to balance system .mdl
• Most of the current analysis time is interacting between three codes
  – Simulink-native (S-functions?) Cantera would help
  – Better S-function documentation or examples would help move this along
Thanks!

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Recommendations

• Cantera/mex interface does not always build correctly
  – May be a Cantera issue
  – and/or mex issue
  – and/or Macintosh issue (different versions of gcc, Tiger, etc.)

• Macintosh version can be much better
  (although some of these issues go beyond the scope of The MathWorks)
  – Can be much more than just a Unix/X11 port
  – Native Aqua, Quartz and other Mac-specific features
  – Use of AltiVec capabilities
  – Better Excel interface
  – Automatic local parallelization (for multi-processor machines)
  – XGrid