Temperature Measurement in the Challenging Environment of the ISS UPA Distillation Assembly Using Wireless RFID Sensors

Christopher Evans
Marshall Space Flight Center
Installation of the UPA's Distillation Assembly (DA) on the International Space Station (ISS)

Concentric spinning cylinders use centrifugal separation and vapor compression distillation to recover water from urine

ES62 and EV34 are currently developing computational models of the UPA and its components

- Will aid development of future exploration units
- Need experimental measurements inside the system for correlation
- Experiments are performed on ground test article, not ISS flight unit
DA Measurement Challenges

• Rotating cylinders
  – Can’t run wires to rotating parts

• Metal enclosure
  – Blocks radio waves

• Corrosive liquid
  – Blocks some EM radiation
  – Destroys many materials and adhesives
  – Shorts out electronics

• Complex to disassemble/assemble
Potential Solution: RFID Tags

- **Radio Frequency Identification**
- **Wireless**
- “Passive” requires no battery
  - Powered by radio waves from the reader, senses and transmits information when actively read
- **Compact**
- Can be encapsulated for protection from harsh environments
- Can include various sensors
- **Limitations**
  - Short read range (a few feet)
  - Signal blocked by metal

Radio signal from reader supplies power to tag
Tag responds via backscatter radio
RFID Implementation Concept

- Passive temperature sensors, antenna/readers wired to outside
- 2 antennas, 8 sensors: 4 inside evaporator, 4 outside condenser
First Phase: Feasibility Study

• Test & model RFID sensor performance in DA-like conditions
  – Sensors & reader inside metal cylinder
  – Sensors along narrow passage
  – Sensors immersed in pretreated urine

• Contractor
  – Phase IV Engineering
    • Specializes in custom RFID sensors
    • Performed tests and modeling for feasibility study
Feasibility Study Results: Outer Condenser Location

- Experimental sensor read tests in between aluminum cylinders with DA dimensions

- Simulations of RF field strength in passage

- Tests show satisfactory field strength and read performance
Feasibility Study Results: Inner Evaporator Location

- Experimental tests of sensor reads while immersed in water and pretreated urine

- Tests show even a thin liquid layer completely blocks the signal
- **Possible workaround**: custom sensor with antenna raised above liquid level
- Energy harvesting may also be an option
Installation

- Hardware developed and installed by Phase IV Engineering
- Tags encapsulated in Duralco 4525N epoxy (inside evaporator) and Silicone Nusil EPM-2410 (outside condenser)
  - Curved to fit wall and steer fluid around the sensor
- Installation completed Oct. 2014

Photos by Phase IV Engineering, Inc.
Preliminary Results

- **Tested without fluid (dry) after installation Oct. 2014**
  - Successful communication with all sensors in a dry system with spinning centrifuge

- **Tested with wet system (nominal operation) early 2015**
  - Confirmed communication with 7/8 sensors
  - Geometry affects performance
    - Better read rate for evaporator sensors in the center near antenna, lower rate for sensors at ends
  - Software tweaks may improve performance
Wireless Data Analysis

- Many outliers in raw data
  - Demanding environment and read behavior
- Filtering
  - Can identify and remove outliers with moving statistics
    - Determine moving average and standard deviation within a window of data
    - Remove points that are outside a specified number of standard deviations from the mean (confidence interval)
  - Multiple filter passes remove more outliers
  - Different window sizes allow for fine vs coarse filtering
- Filter software is still evolving
Results and Findings

- Steady evaporator temperatures indicate stable phase change
- Temperature gradients
  - Highest temperatures near motor
  - Generally higher temperatures in condenser than evaporator
- All wireless sensors within ~4-7°F range
  - 2-5 degrees F for evaporator or condenser alone
  - Quoted design for DA has condenser >10°F hotter than evaporator
- Regular periodic fluctuation of ~1°F visible in all sensors
  - Also seen in DA thermocouples
  - Likely due to PCPA cycling
New Capabilities

• Temperature measurement in sealed, spinning centrifuge filled with caustic fluid
• Determine actual boiling/condensation temperatures
• Observe transient behavior
  – Startup/shutdown effects
  – Stable phase change
  – Response to disturbances
Problems & Issues

- **Noise**
  - Partially filtered by reader, but many outliers remain
  - Affected by operating conditions
  - More outliers in condenser sensors (narrow passage) than evaporator sensors (liquid splashing)
  - Mitigated through post-processing

- **Read rate**
  - Actual readings per minute below target
  - Still sufficient for our work
  - Affected by operating conditions

- **Interference**
  - No issues at first
  - After several weeks, wireless sensor system caused interference with thermocouples elsewhere in the system
  - Likely related to adhesive failure in evaporator and subsequent damage to those sensors
• **Adhesive failure**
  
  – After several weeks of nominal operation, 3/4 evaporator sensors detached from the wall and failed
    
    • Condenser sensors (silicone adhesive) remained attached
  
  – Possible causes
    
    • Chemical – harsh chemicals may have damaged adhesive
    
    • Mechanical – force of moving fluid may have pulled sensors off
    
    • Material – adhesive may not have bonded well to wall
  
  – Rapid development schedule left insufficient time for full material compatibility tests. Abbreviated tests were done instead.
Conclusions & Lessons Learned

• A wireless RFID-based sensor system was successfully developed and integrated into the Urine Processor Assembly ground test article.

• The sensors have provided the first-ever temperature measurements of the evaporator and condenser regions of the Distillation Assembly during operation.

• The sensors provide real-time data on transient behavior within the DA and insight into temperature gradients in the system. This will allow for better validation of computational models of the DA and UPA.

• Several drawbacks and issues with the RFID sensing system were identified, including noisy data, slower than expected read rates, and the potential for interference with other equipment.

• A method for post-process filtering using moving statistics was developed and implemented to reduce the amount of noise in the wireless data.

• The failure of one of the sensor adhesives shows the difficulty of ensuring material compatibility, and the importance of testing.
Future Work

• Additional UPA testing with RFID sensors
• Improve filter software
• New sensors for the evaporator
  – Use silicone adhesive and water rather than pretreated urine

• Suggested upgrades for future RFID sensors
  – Better real-time filtering
  – Improve design to withstand high g-forces
  – Improve signal strength and read/transmit speed
System Specifications

• **Components**
  – 8 metal-mount RFID sensors
    • Thermistor-based temperature measurement
  – 2 patch antennas
  – 1 reader
  – Operating software

• **Sensor capabilities**
  – Temperature ranges: 65-130°F, 100-200°F
  – Accuracy: ±1°F
  – Read rate
    • Target: 6 reads/min
    • Actual (average): 0.5-2 reads/min

• **System development cost: <$100K**
Distillation Assembly Overview

Stationary Bowl

Condenser

Evaporator

Superheated Steam @150°F

Urine/Pretreat Return @85°F

Product H₂O @97°F

External Heaters prevent condensation in stationary bowl volume

Centrifuge rotates at 220 rpm to achieve positive phase separation

Pretreated urine boils at ~32mmHg pressure

Condensing steam surrenders latent heat of condensation

External Heaters prevent condensation in stationary bowl volume

Centrifuge

Rotary Lobe Compressor

Motor

Water Vapor @85°F

Urine Pretreat Supply