CEEE CENTER *for* ENVIRONMENTAL ENERGY ENGINEERING

Paper #2302: Transient Multiphysics Modeling of a Robotic Personal Air Conditioning Device

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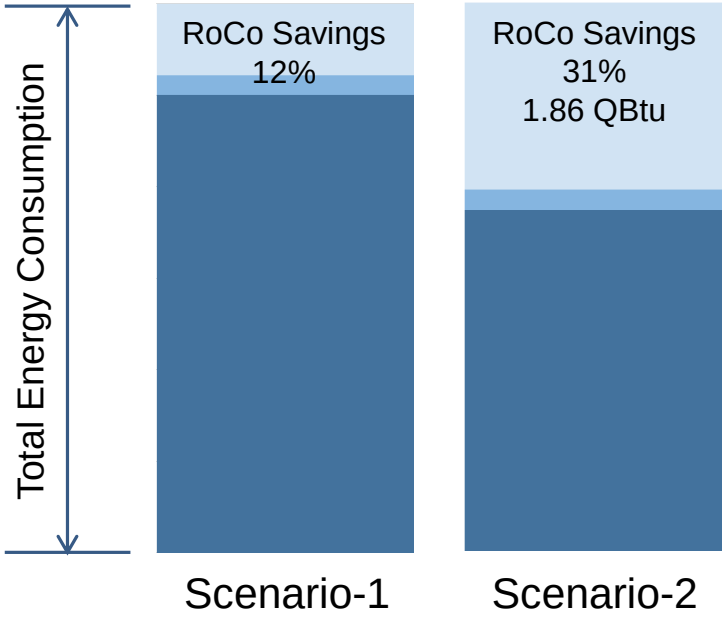
Contents

- Introduction
- Four Conceptual Cooling Systems
- System Modeling
  - Heat Transfer Modeling
  - Battery Modeling
  - Mechanical Modeling
- Results and Discussions
- Conclusions

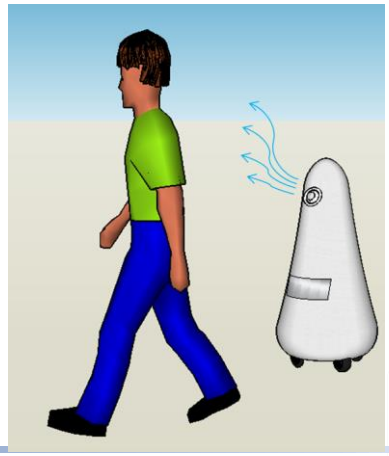
INTRODUCTION

Technology

- Challenges with existing systems
  - Weight, bulkiness;
  - Limited mobility range
  - Short operating times
  - Limited air flow directionality
  - Limited appeal
- RoCo Technology
  - Personal ‘attendant’ for thermal comfort
  - Cooling and heating through one or more robotically controlled air nozzles
  - Highly portable, can follow
  - Integrates thermal storage
  - Multiple implementations and price points

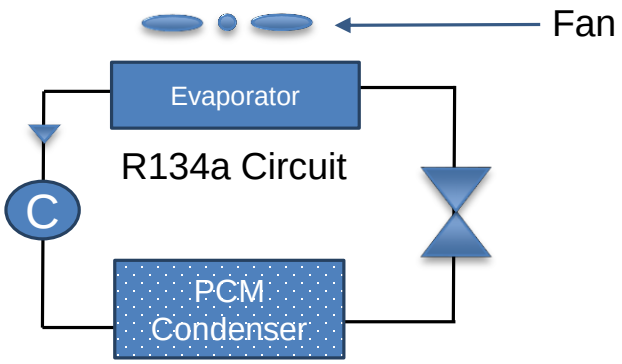


Savings from expanded set points for same comfort

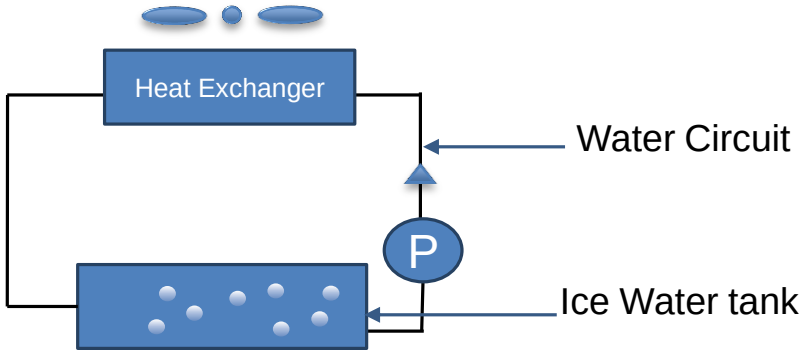


MULTIPHYSICS MODELING

RoCo Systems

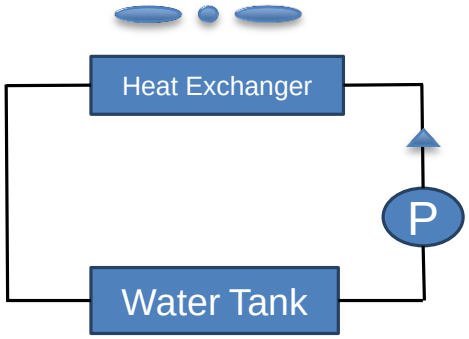


Vapor Compression System

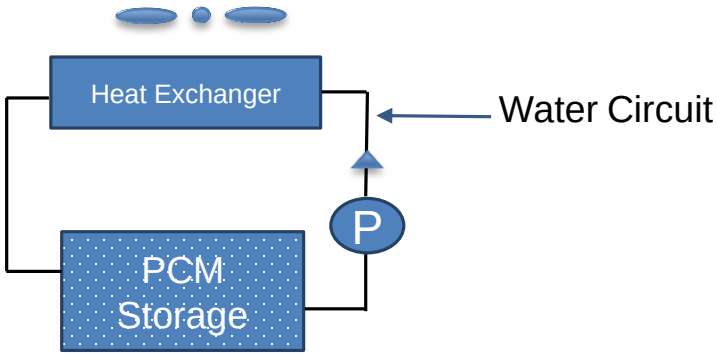


Ice Tank System

C: Compressor, P: Pump



Water Tank System



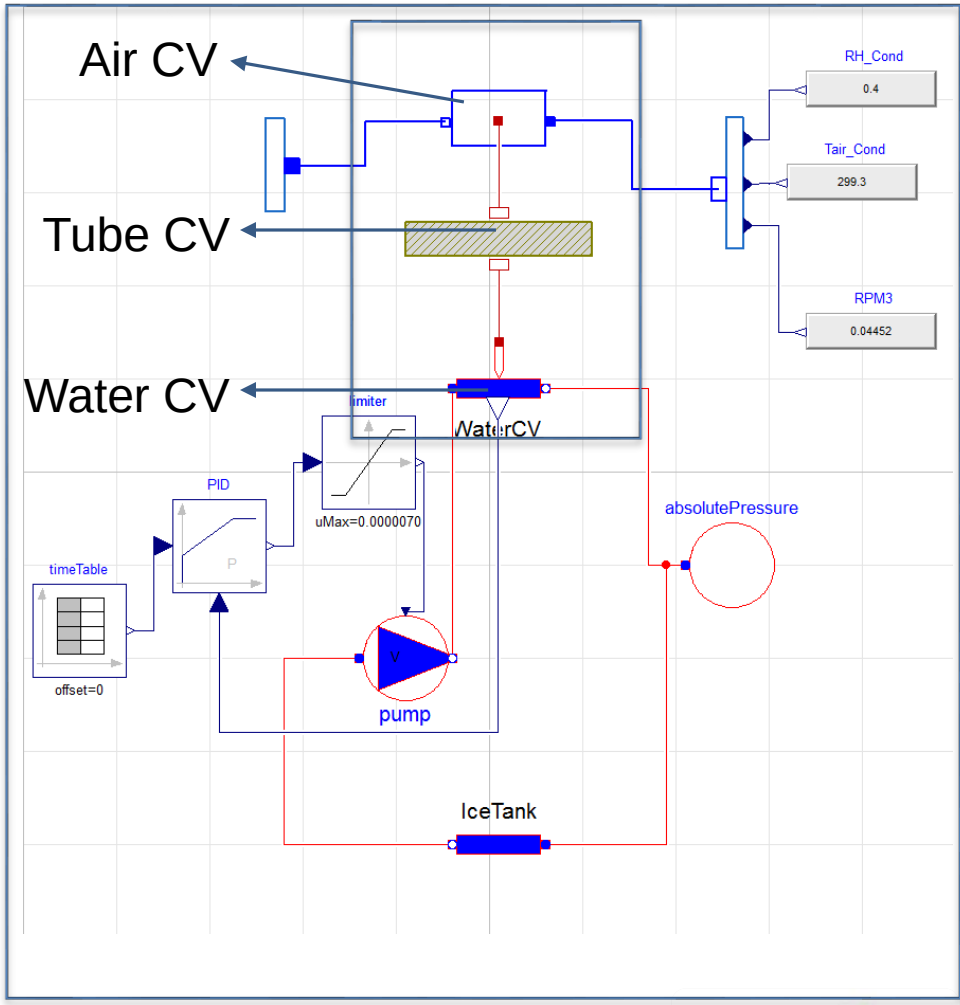
PCM Based System

Modeling Considerations

- Systems designed to deliver 170 W of cooling for 2 hours
- Transient modeling using Modelica
- System simulations using CEEE Modelica Library and Modelica Standard Library
- Components developed for mechanical modeling, battery modeling and water to air heat exchanger
- Weight and cost calculations using component database in Excel

Heat Transfer Modeling

- Finite volume discretization to capture air to water heat transfer
- Churchill correlation with a smoothing function for waterside heat transfer coefficient
- Instantaneous mixing assumed in water tank and ice tank
- Same airside HX used for both VCC and Water systems



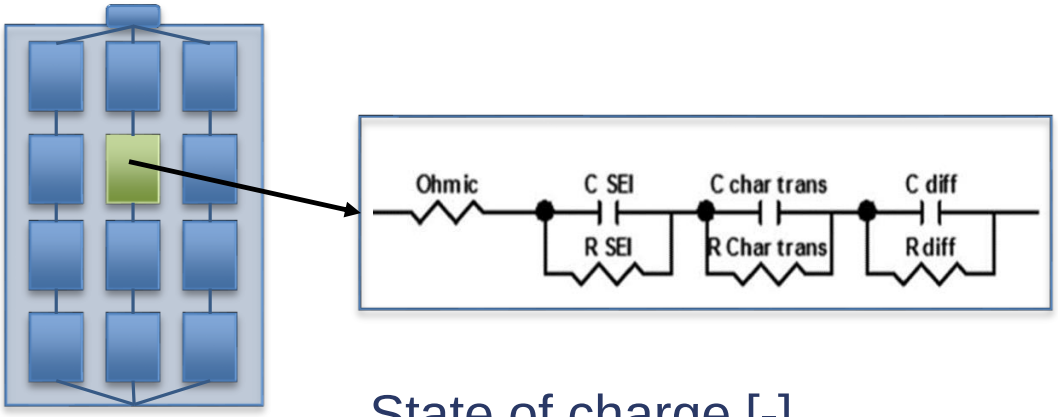
Battery Modeling

- Transient battery performance using equivalent R-C circuit approach
- Degradation of battery with usage calculated

$$P_{cell} = \frac{P_{bat}}{n_s n_p}$$

$$I_{bat} = n_p * I_{cell}$$

$$V_{bat} = n_p * V_{cell}$$



Cell Capacity [Coulombs]

$$C = C_0 + k_{C,Qabs} Q_{abs} + k_{C,t} Q_t$$

Charge dissipation aging

Calendar aging = 0

State of charge [-]

$$SOC = SOC_0 - K * \frac{(Q_{abs} - Q_{ini})}{C}$$

Thermal dissipation factor

Valentin Muenzel, et al, "A Comparative Testing Study of Commercial 18650-Format Lithium-Ion Battery Cells", *Journal of The Electrochemical Society*, 162 (8) A1592-A1600 (2015)

Battery Modeling (Cont'd)

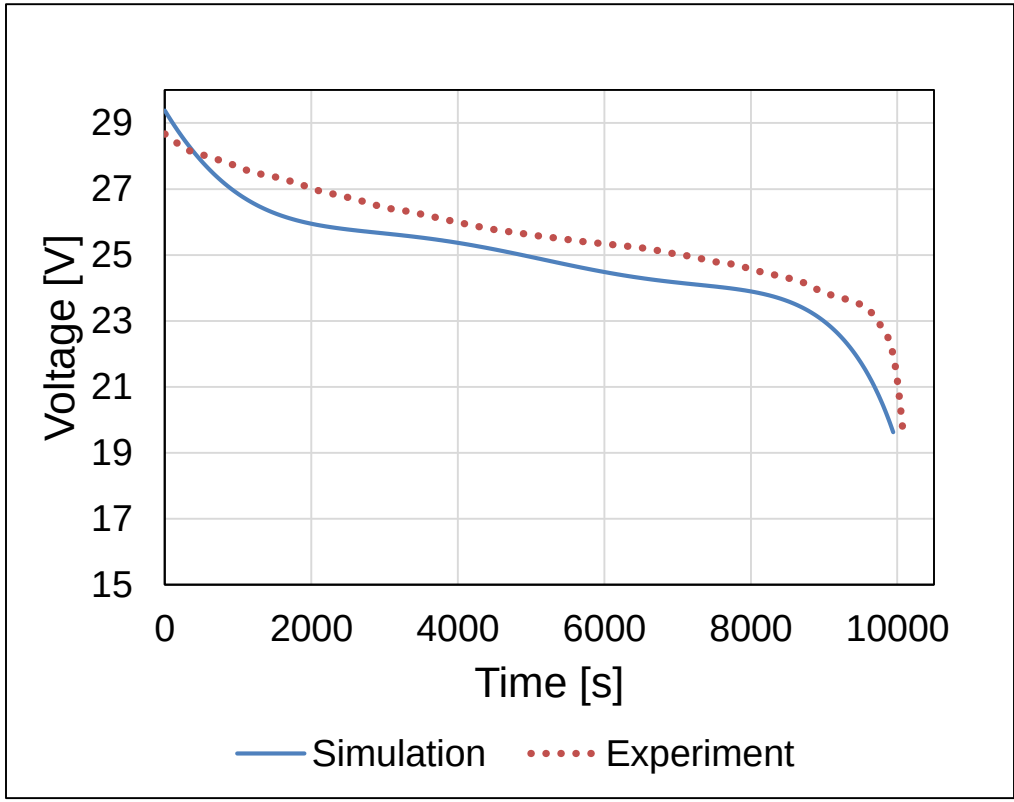
$$V_{cell} = f(SOC)$$

f(SOC) obtained from discharge characteristics supplied by battery manufacturer

$$P_{cell} = V_{cell} * I_{cell}$$

$$I_{cell} = \frac{V_{cell} - V_{sei} - V_{char,tran} - V_{diff}}{R_{ext} + R_s}$$

$$V_x = \min(I_{cell} * R_x, \frac{(Q_{abs} - Q_{ini})}{C_x})$$



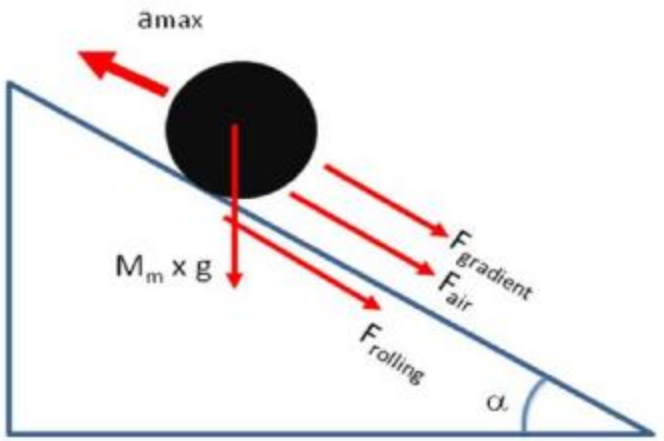
R_x, C_x values are obtained from EIS experiment and also have degradation factor

Model validated against a battery-run constant power drawing circuit of 70W

Mechanical Modeling

- Battery power consumed while moving is estimated by force balance
- Minimum weight of thermal storage to run each system obtained from simulation
- Net weight of each system obtained by adding other component weights

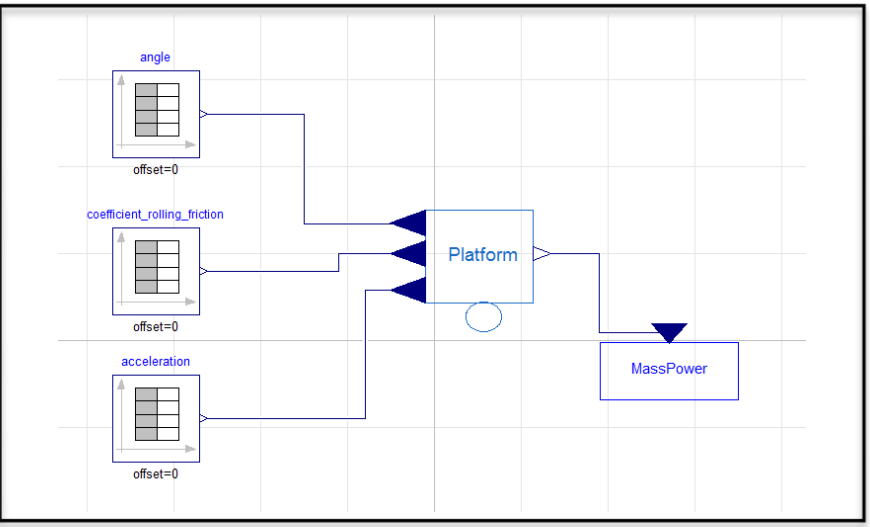
$$Power = F_{Total} * velocity$$
$$F_{Total} = F_{gradient} + F_{air} + F_{rolling} + F_{translation}$$
$$F_{gradient} = mass * g * \sin(\alpha)$$
$$F_{air} = 0$$
$$F_{rolling} = f_{rolling} * mass * g * \cos(\alpha)$$
$$F_{translation} = mass * acceleration$$

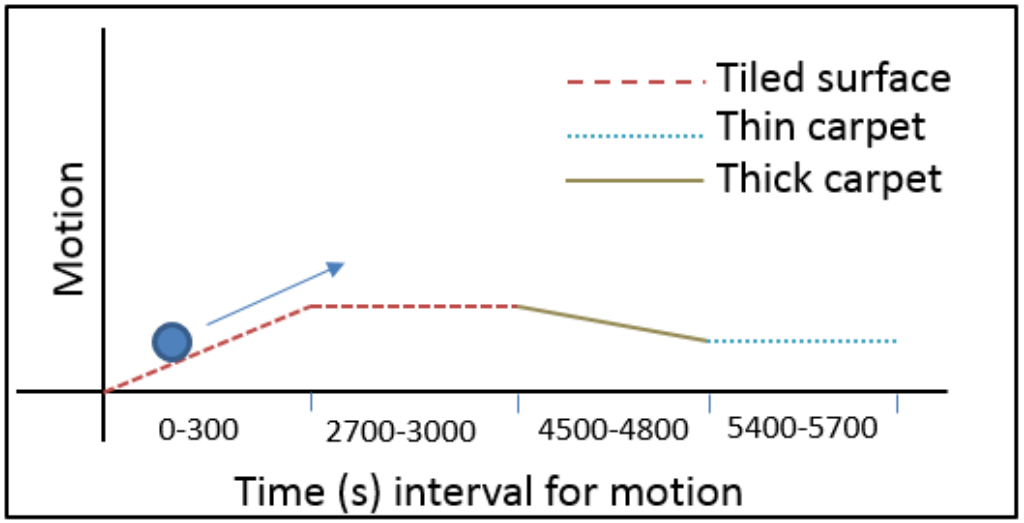


Muhammet Gonullu (2013), "Development of a mobile robot platform to be used in mobile robot research", *MS Thesis, Middle East Technical University*

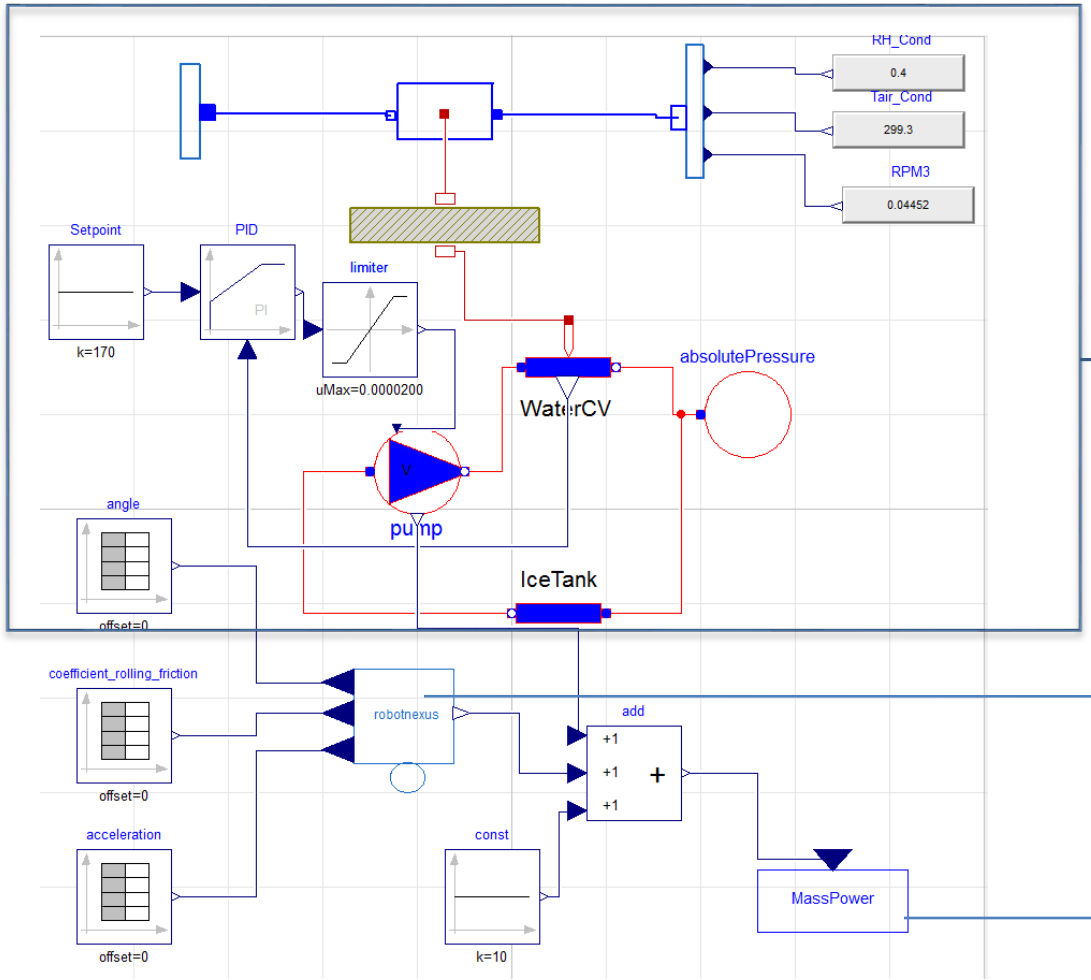
Sample Run for Robotic Platform

- Typical operation involves non-uniform motion over different surfaces with varying inclinations
- Behavior captured using time varying inputs for inclination angle, coefficient of rolling friction and acceleration





System Multiphysics Model



Heat transfer components

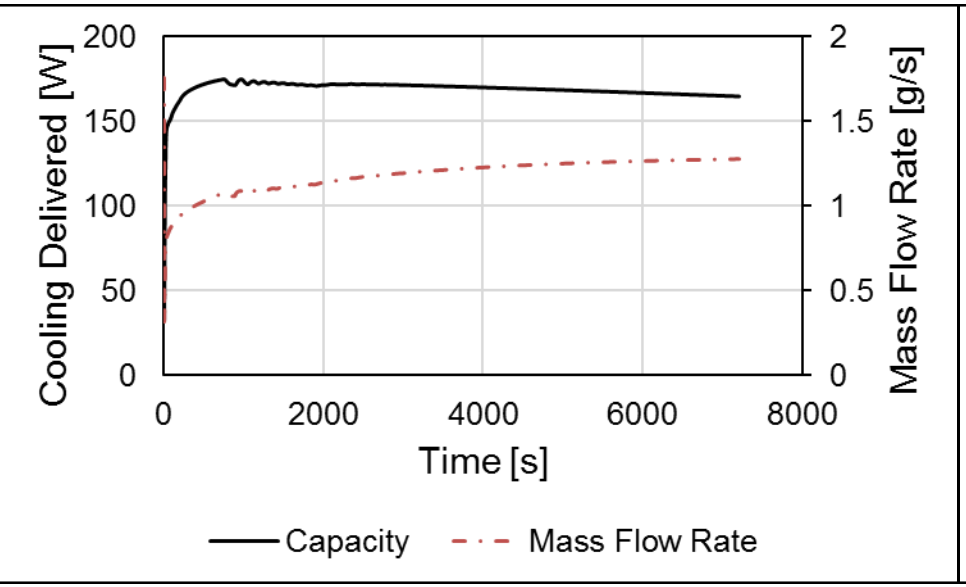
Platform

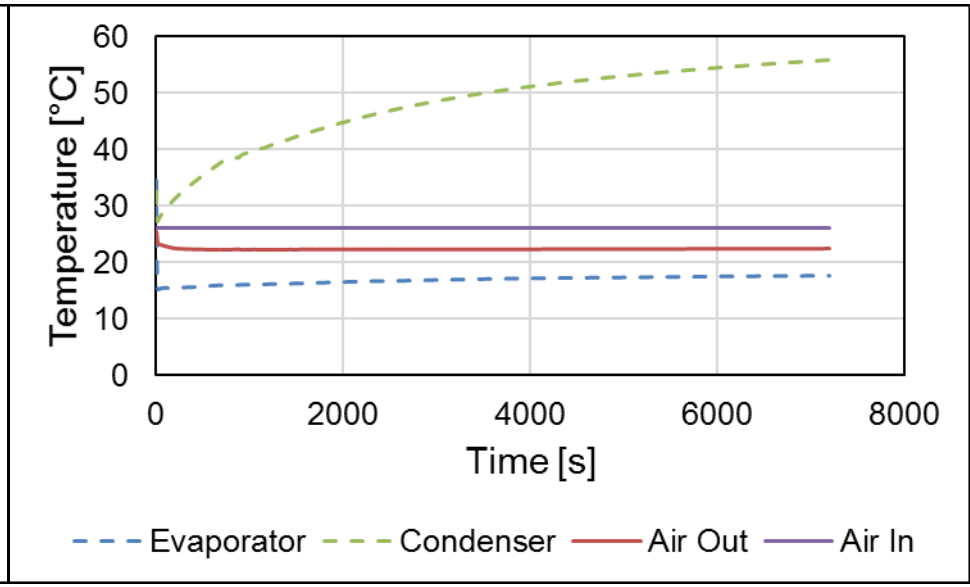
Battery

RESULTS AND DISCUSSION

Vapor Compression System

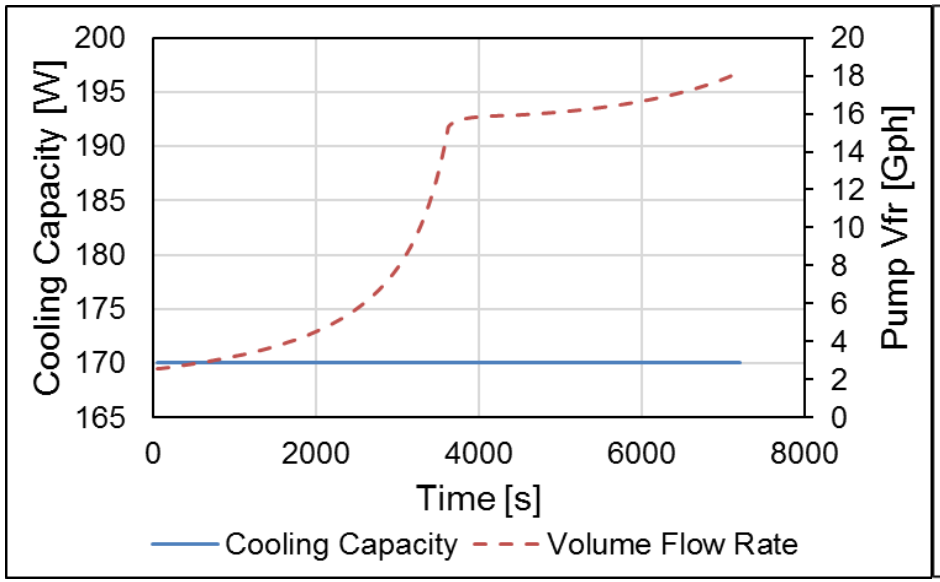
- PCM Mass = 6.0 kg, Latent heat = 210 kJ/kg
- Condenser heat captured in PCM
- Orifice tube as expansion device
- Refrigerant = R134a

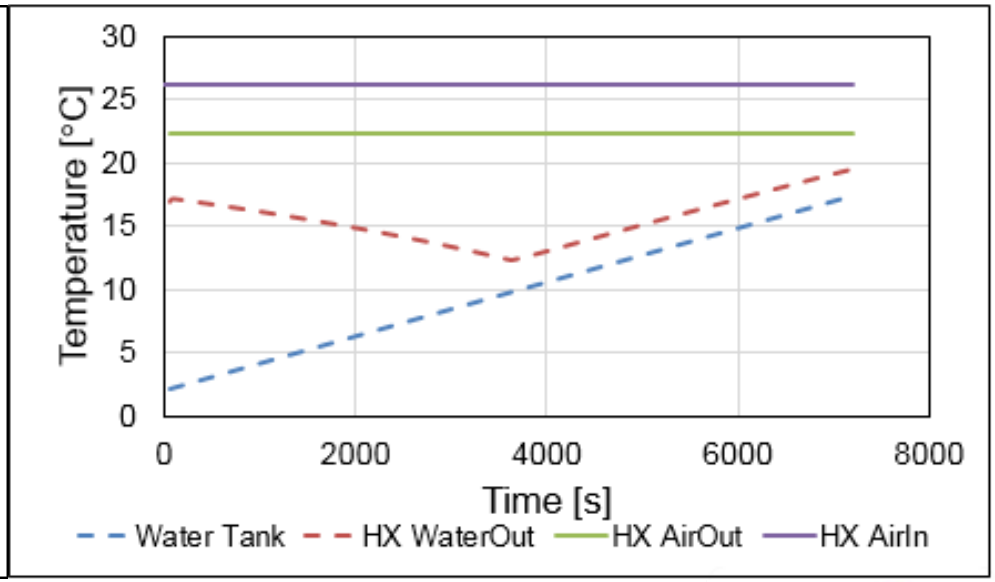




Water Tank System

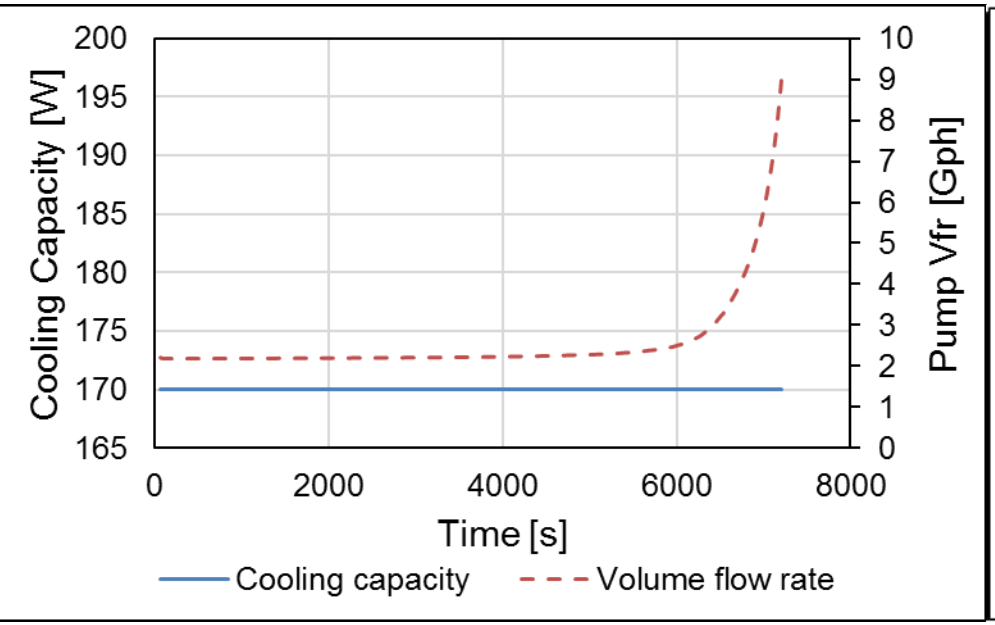
- Crossflow Air to Water HX, with higher thermal resistance on waterside
- Initial Water Amount = 19 kg
- Initial Water Temperature = 2°C

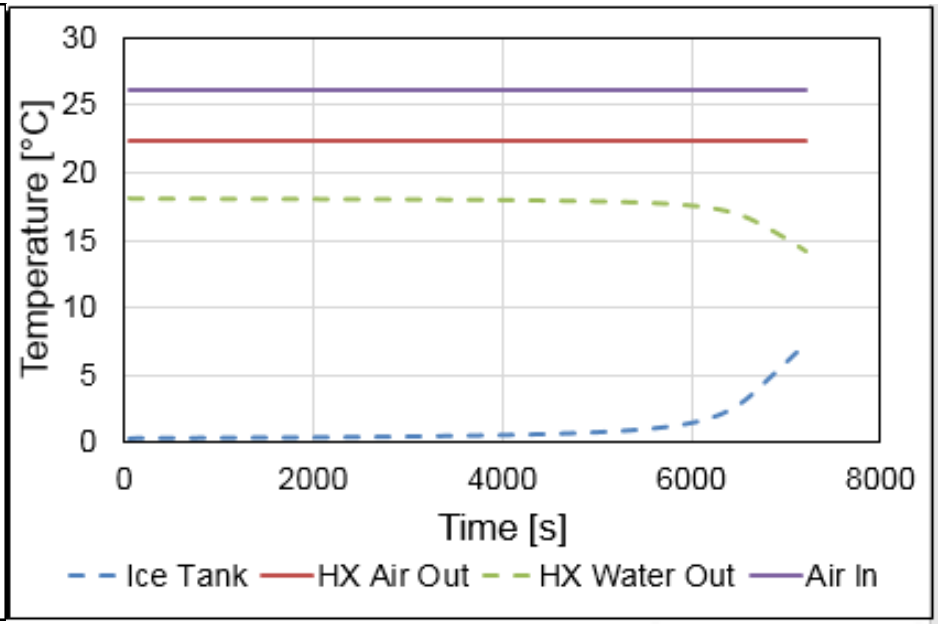




Ice Tank System

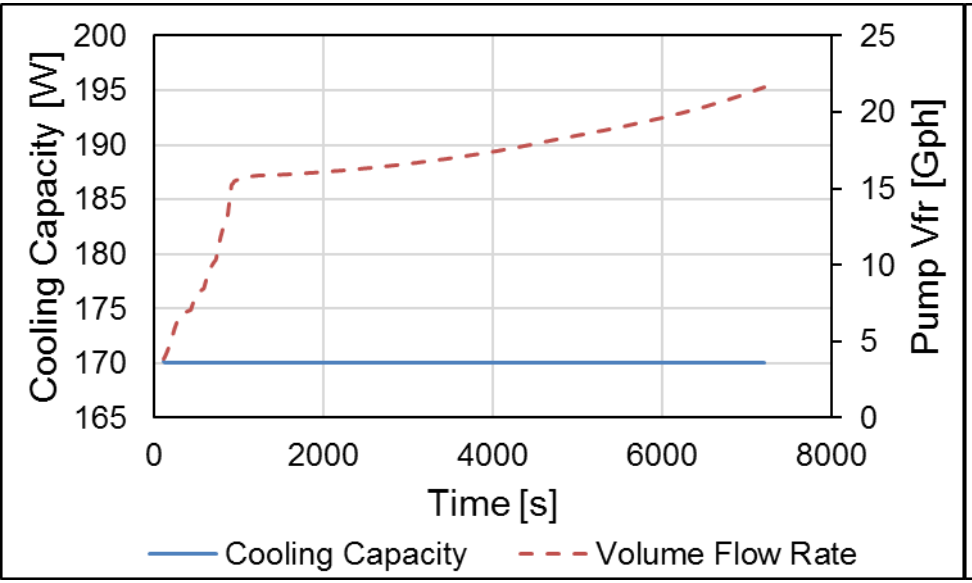
- Initial water in tank = 3 kg
- 240 ice spheres (3.1 kg)
- Constant air inlet temperature = 26ºC

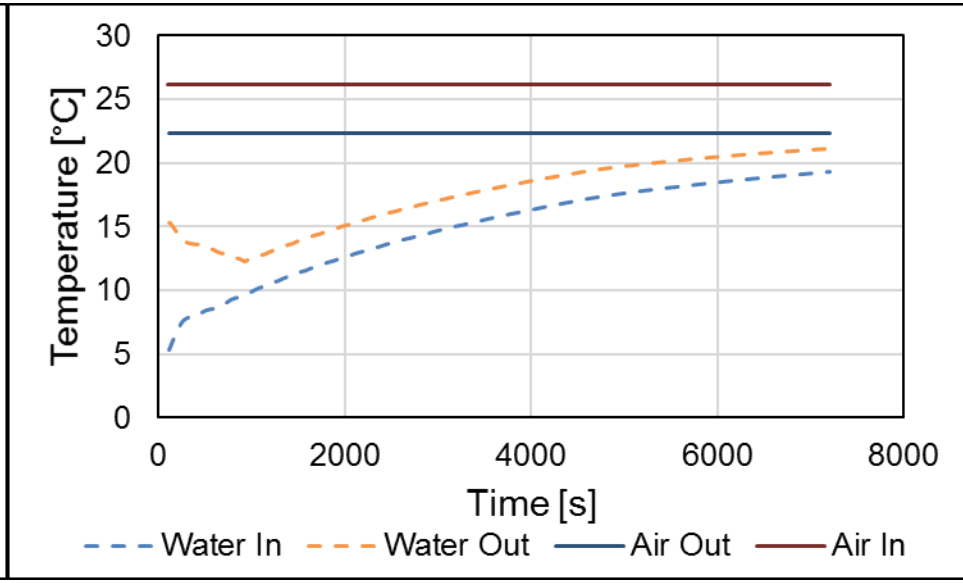




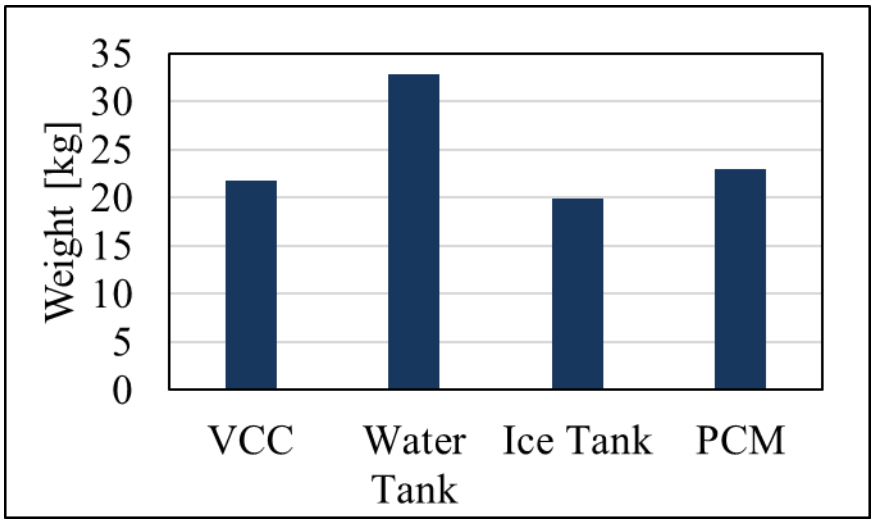
PCM System

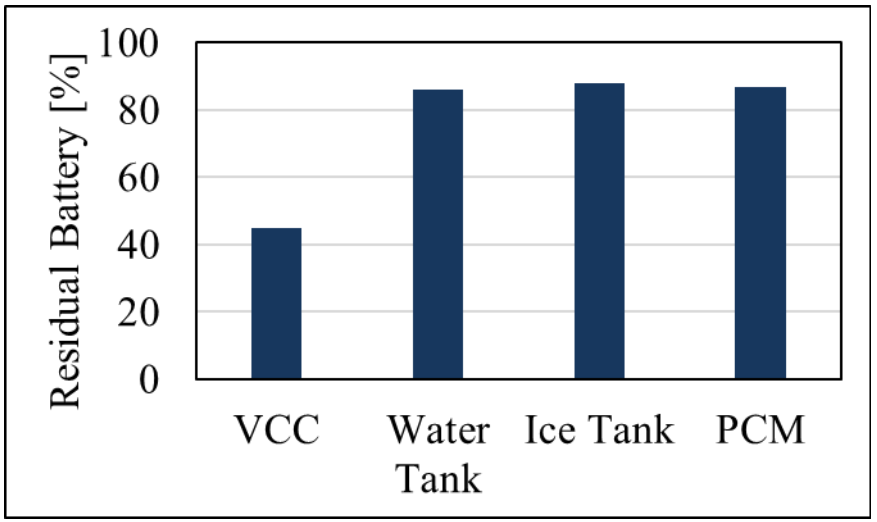
- PCM mass = 5.6 kg
- Latent heat = 220 kJ/kg
- PCM melting temperature = 6°C

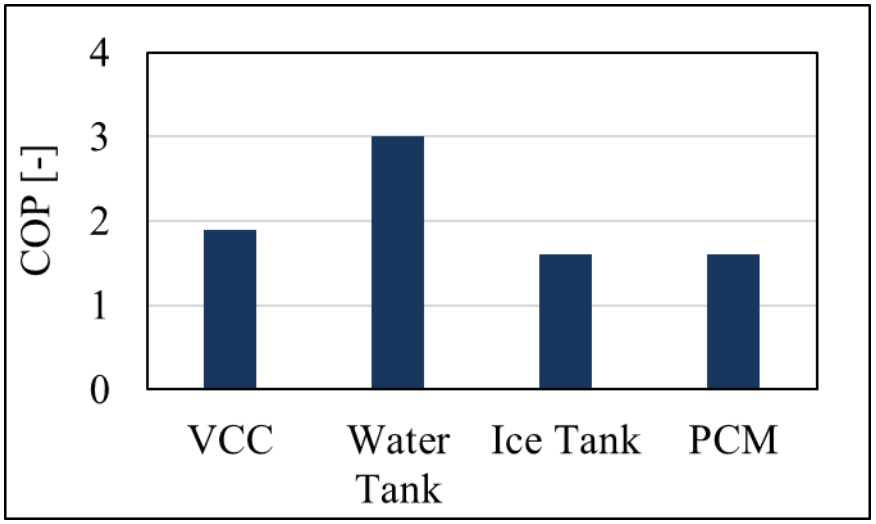


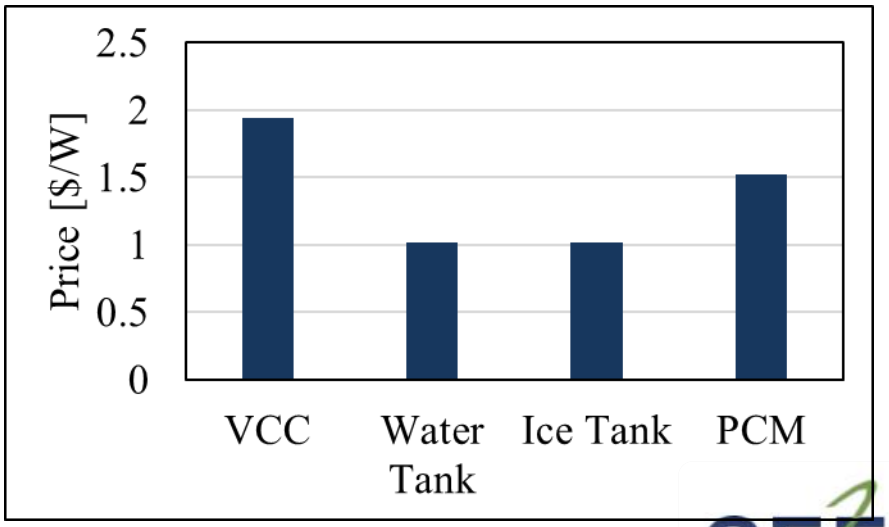


System Comparison









Conclusions

- Vapor compression system
  - Compact, high COP, high cost
  - Minimal user input for thermal recharge
  - Self contained recharge mechanism enabling application to larger locations
- Water tank system
  - Bulky, highest COP, lowest cost
- Ice tank system
  - Very compact, lowest COP, lowest cost
- PCM system
  - Compact, lowest COP

Summary

	VCC	Water tank	Ice tank	PCM
Weight				
Battery Consumption				
COP				
Price				
Thermal recharge ease				
Applicable locations				

 Advantageous

 Dis-advantageous

Thank You

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References

1. Churchill, S. (1977). Comprehensive Correlating Equations for Heat, Mass and Momentum Transfer in Fully Developed Flow in Smooth Tubes. Industrial and Engineering Chemistry Fundamentals, Vol 16(1), 109-116
2. Dhumane, R., Du, Y., et al (2016). Transient Modeling of a Thermosiphon based Air Conditioner with Compact Thermal Storage: Modeling and Validation. 16th International Refrigeration and Air Conditioning Conference, Purdue, Indiana, USA
3. Einhorn, M., Conte F., et al (2011). A Modelica Library for Simulation of Electric Energy Storages. Proceedings of 8th International Modelica Conference 2011, Dresden, Germany
4. Gnielinski, V. (1975). New Equations for Heat and Mass Transfer in Turbulent Pipe and Channel Flow. Forschung im Ingenieurwesen, Vol 41(1), 8-16.
5. Hao, Y., Tao, Y. (2002). Heat Transfer Characteristics of Melting Ice Spheres under Forced and Mixed Convection. Journal of Heat Transfer, Vol 123, 891-903
6. Haumer, A., Kral, C., et al. Modelica Documentation. Last Accessed April 28, 2016: http://modelica.github.io/Modelica/om/Modelica.Thermal.FluidHeatFlow.html
7. Hoyt, T., Kwang H., et al (2005). Energy savings from extended air temperature setpoints and reductions in room air mixing. International Conference on Environmental Ergonomics 2009, Boston, USA
8. Incropera, F., DeWitt, D. (2007). Fundamentals of Heat and Mass Transfer (6th Edition). New York, USA. Wiley
9. Muenzel, V., Hollenkamp, A., et al (2015). A Comparative Testing Study of Commercial 18650-Format Lithium Ion Battery Cells
10. Qiao, H., Aute, V., et al (2015). Transient modeling of a flash tank vapor injection heat pump system – Part I: Model development. International Journal of Refrigeration, Vol 49, 169-182

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