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Transient Multiphysics Modeling of a Robotic Personal Air-Conditioning Device

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ABSTRACT

The Roving Comforter (RoCo) is an innovative personal thermal management technology currently being developed at the University of Maryland. It is an ultra-low cost, autonomous, battery powered heat-pump system that provides comfort to a single or multiple individual by discharging conditioned air through adjustable nozzle(s). To minimize the system cost and maximize system performance, careful selection of components is required for battery, robotic platform as well as the cooling mechanism. Hence system level calculations which incorporate thermodynamics, electricity, cost as well as the weight restrictions at the same time is being developed to obtain the optimum design. This paper explores four different cooling mechanisms (chilled water, ice water mixture, melting phase change material and vapor compression cycle) and discusses their potential applications in the RoCo. Preliminary calculations have revealed the chilled water based system to have a lowest bulk manufacturing cost of \$173 while the VCC model to have the highest cost of \$320. Weights of the prototypes vary from 19.2 kg for the ice water model to 30 kg for the chilled water model. Battery consumption is calculated to be in between 24-26% of total capacity with VCC consuming the highest and ice tank consuming the lowest. The challenges faced in making each mechanism operational are discussed with their possible solutions. System parameters to operate each mechanism for a sample two hour cooling operation are obtained from the model. Finally, one of the concepts is chosen by weighing various advantages and disadvantages to power the cooling mechanism for RoCo. The paper provides insight into tradeoffs from various domains to obtain the final design.

1. INTRODUCTION

The Roving Comforter (RoCo) is a personal attendant for comfort, capable of following a single or multiple person(s) autonomously and delivering comfort by directing hot or cold air as required through automatically controlled nozzles (Figure 1). It enables buildings to operate with elevated set-point temperatures of 4°F without compromising on personal comfort and thus serving as the ultimate local thermal management system to deliver energy savings in the range of 20-40% depending on climatic conditions (Hoyt, 2005). It is highly affordable with excellent consumer appeal, making it a potential breakthrough product for large scale energy savings.

The RoCo is designed to deliver only cooling in the first prototype, with heating capability implemented in upcoming versions. To achieve project objectives, the cooling mechanism needs to deliver continuous cooling for desired time period and at the same time be cost effective, energy efficient, compact and portable. Four possible concepts, in which refrigerant flows cyclically through a circuit, are considered to deliver cooling for RoCo. Three of them use water as the refrigerant while the fourth uses R134a. Modeling is carried out to understand behavior and challenges involved in using each of these mechanisms. The prototype from each cooling mechanism is designed to deliver 170 W of cooling for an operation time period of two hours. The maximum permissible weight is 30 kg.

Since it is portable, RoCo needs a single unified battery pack to address all its power inputs whether they are related to cooling mechanism, controls or mobility. Increased battery pack size leads to longer operation period but adds to

the net weight. This would lead to lesser weight allowance for thermal storage, since total weight of the device is constrained. Hence an accurate model for battery pack is critical for the design.

Finally, since RoCo is an affordable consumer product, its component cost also plays an important role in design decisions. The calculations for large scale manufacture cost rely on some reasonable assumptions for most parts and are intended for the order of magnitude comparison only. With the tools and methodology detailed in the upcoming passages for cost it should be possible for any person to recreate calculations for accurate results if desired.

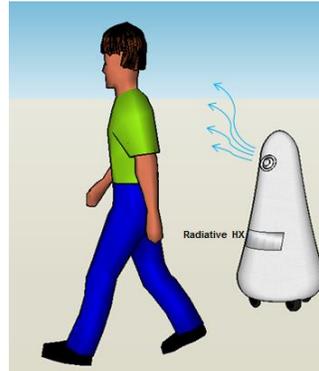


Figure 1: RoCo in use

The four cooling mechanisms to deliver cooling are vapor compression cycle (VCC), chilled water, water mixed with ice and melting phase change material (PCM). Schematic of concepts based on each of these can be seen in Figure 2. Transient modeling for all concepts as well as battery modeling is carried out using Modelica® which is an object oriented, acausal, equation based modeling language to conveniently model complex multi-physics systems. For cost and weight calculations, Microsoft Excel® is used to develop a comprehensive component database to facilitate easy understanding of system level comparisons between various models.

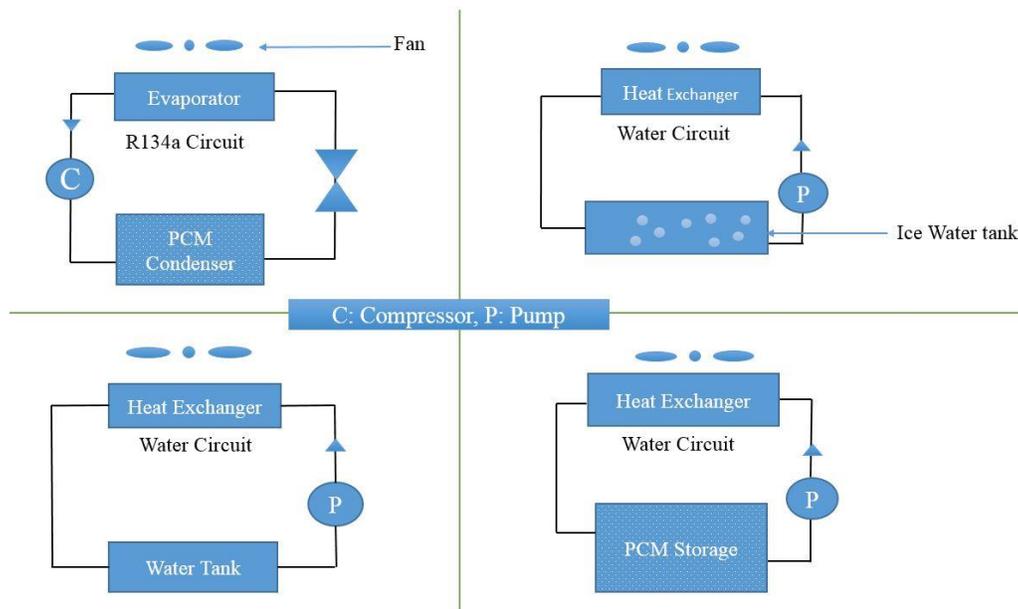


Figure 2: Schematic of the four concepts for cooling mechanism: (Top Left: Vapor Compression Cycle, Bottom Left: Water Tank, Top Right: Ice Tank, Bottom Right: PCM Based)

2. THERMODYNAMIC PERFORMANCE MODELING

Calculations are carried out for these four cooling concepts to compare their compactness. A standard cooling of 170 W is considered to be delivered for 2 hours by each cooling mode and the weight of each system is determined by summarizing weights of the components that make up the system. The thermal storage is sized to store 1224 kJ of heat for each concept.

2.1 Vapor Compression Cycle

The first concept is miniature Vapor Compression Cycle (VCC) based cooling mechanism. It uses a phase change material (PCM) to store the waste heat generated in the condenser. A fan blows air through the evaporator and is then directed by a nozzle on the individual (Figure 2, Top Left).

The mass of components is obtained from the component database developed in Excel. To calculate the mass of PCM, the net heat storage is equated to the sensible as well as latent heat storage for the block of PCM as shown in Equation 1. The mass of PCM obtained required is 5.2 kg and a 50% margin is added to account for the deviation may happen in real-time operations. The weight of VCC is calculated by adding up the weights of remaining components to 21.1 kg.

$$E_{st} = mc_{p,s}\Delta T_s + mh_f \quad [1]$$

The cooling delivered by this option is developed in Modelica by using components developed by Qiao (2015). For PCM heat exchanger, the PCM Control Volume (CV) developed in Dhumane (2016) is connected to a Tube CV which is in turn connected to a Refrigerant CV. R134a is used as refrigerant. The heat released by the condenser is stored in the PCM which is a paraffin-based material. The operating time of this option is limited by the heat storage capacity of PCM. The actual thermal conductivity used in the model is 5 times more than that of the pure PCM material due to those approaches added to reduce the high PCM thermal resistance like addition of copper wool, graphite, spiraling of refrigerant tubes and so on. The concept is able to deliver stable cooling for majority of operation time as shown in Figure 3.

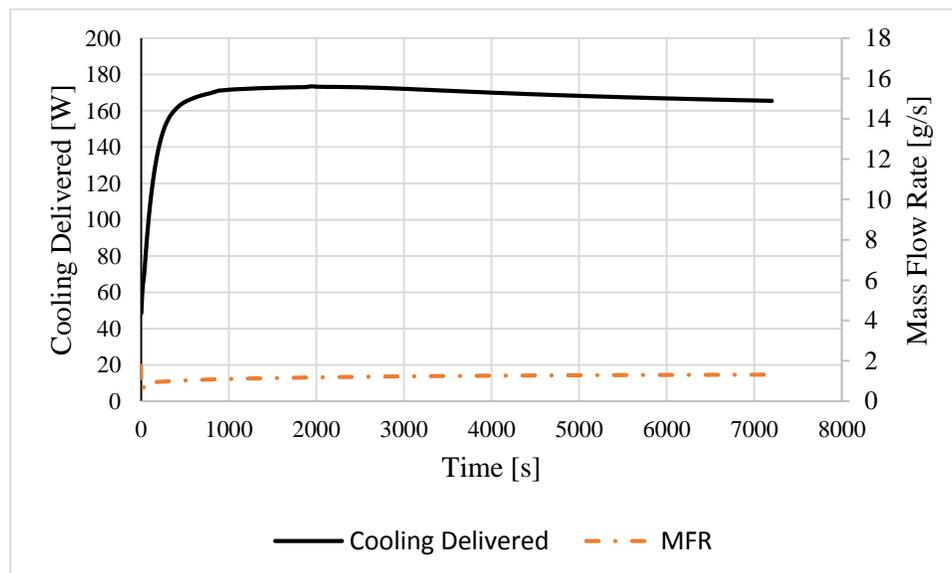


Figure 3: Cooling Delivered by VCC

2.2 Water Tank

The second concept referred to as Water Tank which consists of a tank filled with cold water at 2°C. A pump is used to circulate this water through a heat exchanger. A fan blows air through this heat exchanger and a nozzle delivers it

towards the individual (Figure 2, Bottom Left). The transient modeling of Water Tank concept was done using the components available from the Standard Modelica Library in the Thermal – FluidHeatFlow package (Hauman, Modelica Documentation). Isolated pipe is used as Water Tank while VolumeFlow component is used as pump. However, the component for air to water heat exchanger (AWHX) is developed. AWHX involves three blocks: Airside CV, Tube CV and Waterside CV. The Airside CV and Tube CV are obtained from Qiao (2015).

For water tank concept, 16.2 kg of water with 18 K of temperature rise is able to store the required heat (Equation 2). Adding up the weights of other components, the total mass of this system is 30 kg.

$$E_{st} = mc_{p,l}\Delta T_l \quad [2]$$

The Waterside CV is developed as a finite volume model with energy conservation equation (Equation 3) to calculate the outlet state of water exiting the heat exchanger. Nusselt number in the laminar region is taken as 4.36 as specified by Incropera and DeWitt (2007). For transition region, the Nusselt number proposed by Churchill (1977) is used. Finally, for the turbulent region Gnielinski (1975) correlation is used.

$$\dot{m}_{in}h_{in} = UA_s(T_{tube} - T_w) + m_w c_v \frac{dT}{dt} + \dot{m}_{out}h_{out} \quad [3]$$

Results of cooling capacity vs time for Water Tank is shown in Figure 4. Slight bump in cooling capacity near 4800 s is due to the transition from laminar flow to the transition region of the water circulating in the circuit. To obtain a uniform cooling capacity, the water flow rate from the pump needs to be regulated by controls. For the purpose of this simulation, the values are input manually. However, PID controls may be used to obtain more uniform profile as part of future work. A variable mass flow rate from an 80 gallon/hour pump is sufficient for operation.

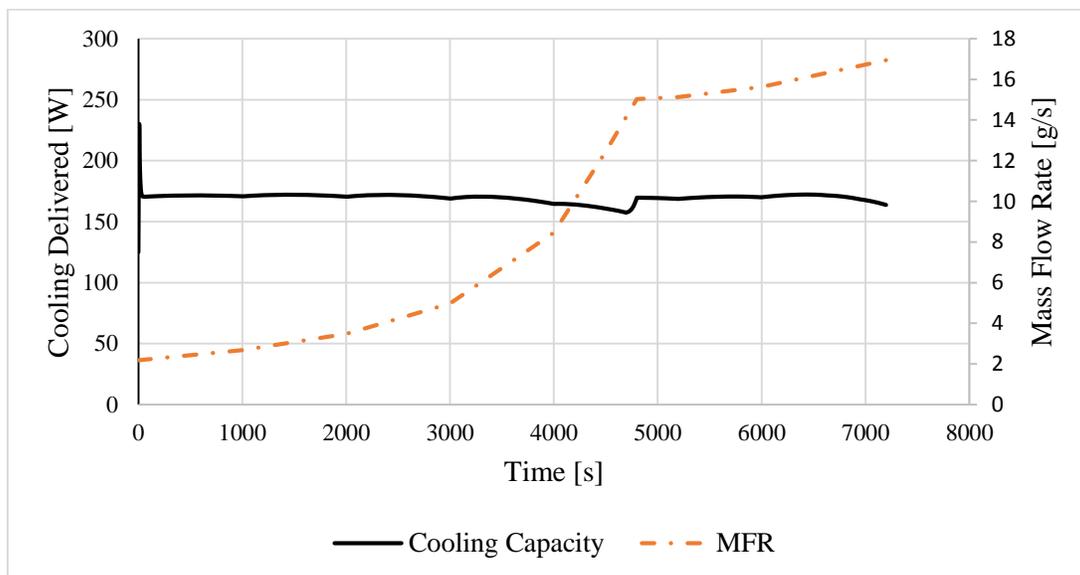


Figure 4: Water Tank Cooling Capacity

2.3 Ice Tank

The third concept referred to as Ice Tank is similar to the water tank concept except that the tank now contains ice cubes in the water instead of just cold water (Figure 2, Top Right). This addition of ice cubes makes tank much more compact than the pure water storage. For modeling Ice Tank, the component for ice tank is developed and used as replacement for the isolated pipe component used in Water Tank model (Section 2.2). The rate of melting of ice depends on the heat captured by it from the water in the tank. For the initial condition, tank water is taken at a slightly higher temperature than the melting point of ice. Ice is modeled as lumped body at its melting temperature. The heat absorbed by ice cube is used to melt ice as given by Equation 4. Rate of melting of ice in flowing water is a complex phenomenon and its exact modeling is unnecessary and beyond the scope of this work. Hence a constant value for heat transfer coefficient of 1000 W/m²-K is used by observing the experimental results presented by Hao and Tao (2002). It is also assumed that the ice melts in such a way that its shape remains spherical at all times. The variation

of its radius with time is calculated from Equation 5. Finally, the energy balance for the Ice Tank is given by Equation 6.

$$\frac{dm}{dt} h_f = U_{ice} A (T_w - T_{ice}) \quad [4]$$

$$n \cdot \rho 4\pi r^2 \frac{dr}{dt} = \frac{dm}{dt} \quad [5]$$

$$\dot{m}_{in} h_{in} = \frac{dm}{dt} \cdot h_f + m_w c_v \frac{dT}{dt} + \dot{m}_{out} h_{out} \quad [6]$$

The ice tank concept provides a lot more variables for optimizing performance like the shape of ice, total mass of ice, initial quantity of water and so on.

For the ice tank concept, it is assumed that 3 kg of water is required to fill in the circuitry. The mass of ice required is calculated so that its latent heat plus the sensible heat portion of the molten water and the initial water amount with 18 K temperature rise is able to store the required heat. The minimum mass of ice required is 2.8 kg. The weight of the ice tank concept is 19.2 kg.

Results of cooling delivered by ice tank are shown in Figure 5. The results are obtained for an ice tank comprising 3 kg of water filled with 500 ice cubes of 15 mm radius. The concept does not require significant variations in mass flow rate like the water tank concept to deliver uniform cooling.

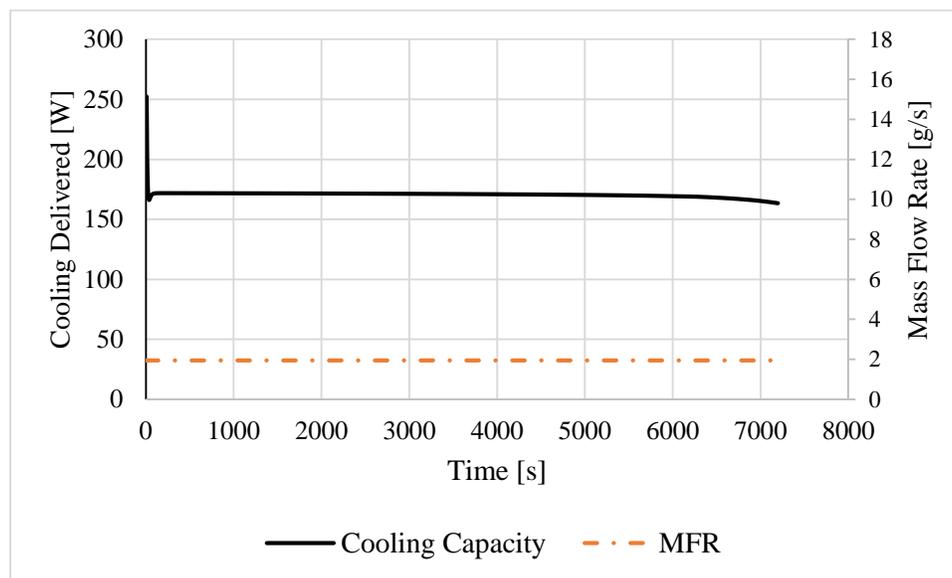


Figure 5: Cooling Delivered by Ice Tank Concept

2.4 PCM Cooled

The final concept is the PCM cooled water cycle. Here the water flowing through the circuit is cooled by the melting PCM (Figure 2, Bottom Right). The PCM used in this case is different from the one used in the VCC based concept in that it delivers cooling instead of storing waste heat. The PCM in the first concept has melting point of 37°C while the one in the last concept has of 5°C. The thermal conductivity of PCM is increased by 5 times to account for the enhancement methods mentioned in Section 2.1

Finally, for the weight of PCM is calculated by taking the ratio of latent heats of the PCM in VCC to the PCM in the water based cycle. The weight of the system for this concept is 23.5 kg.

The development of model for Phase Change Material (PCM) is detailed in Dhumane (2016). The component developed for PCM is connected to the lumped Waterside CV to model the behavior of water based PCM heat exchanger. The other components of the cycle are same as in Water Tank and Ice Tank cycles. Results for the transient behavior for this concept are shown in Figure 6.

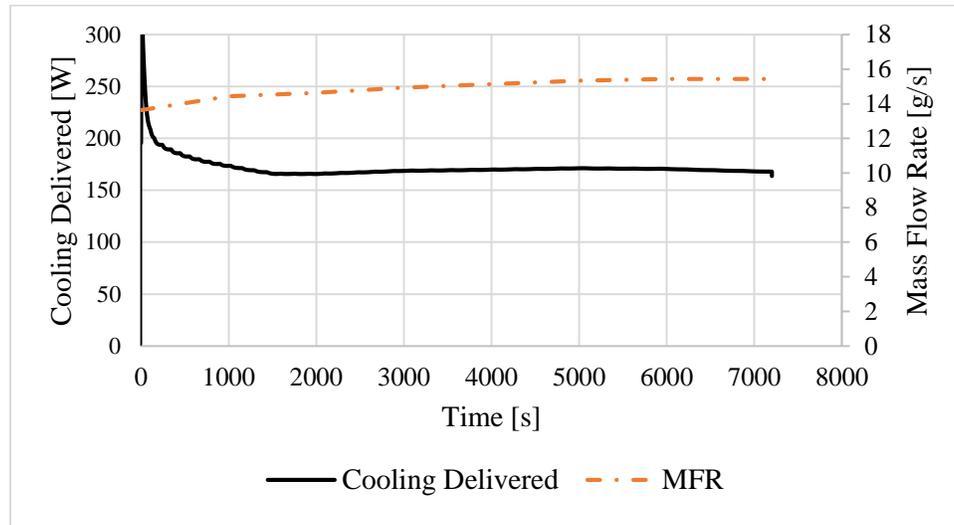


Figure 6: Cooling Delivered by PCM Cooled Concept

2.5 Concept comparison

To compare the compactness of each concept, the weight required for capturing 1224 kJ of heat, or equivalent of providing 170W for 2 hours, by each method is plotted in Figure 7. Taking typical values of coefficient performance (COP) for a freezer as 1.8 and water chiller as 3.8 and incorporating a pump of 4 W and a fan of 6 W, operational COPs of water based systems are calculated. These results along with measured COP of VCC are plotted in Figure 7.

As can also be observed, except for water tank concept all others have the potential for delivering cooling for more than 2 hours if scaled to the weight limit of 30 kg. Calculations for these are carried out by scaling refrigerant tubing, container weight and other components to finally allocate the additional thermal storage amount. The results for this calculations are trivial and not covered for the sake of brevity. The results however are shown in Figure 8.

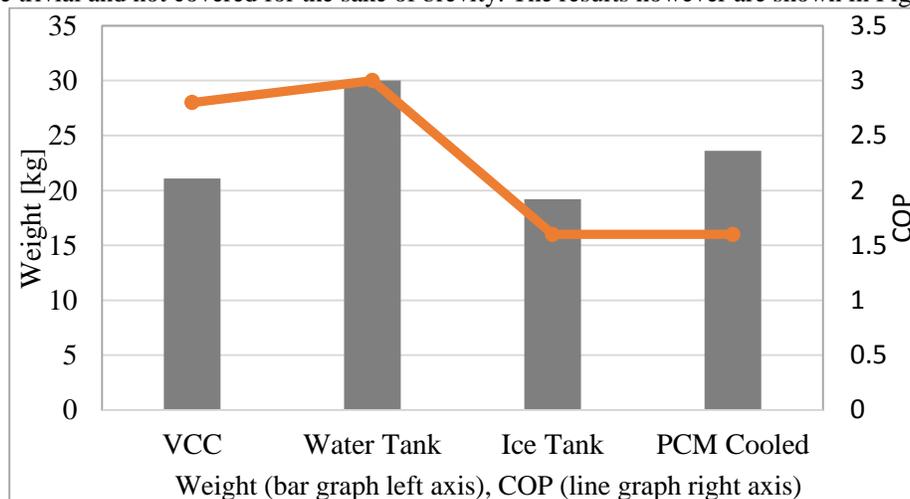


Figure 7: Weight and COP of each concept that delivers 2-hour cooling

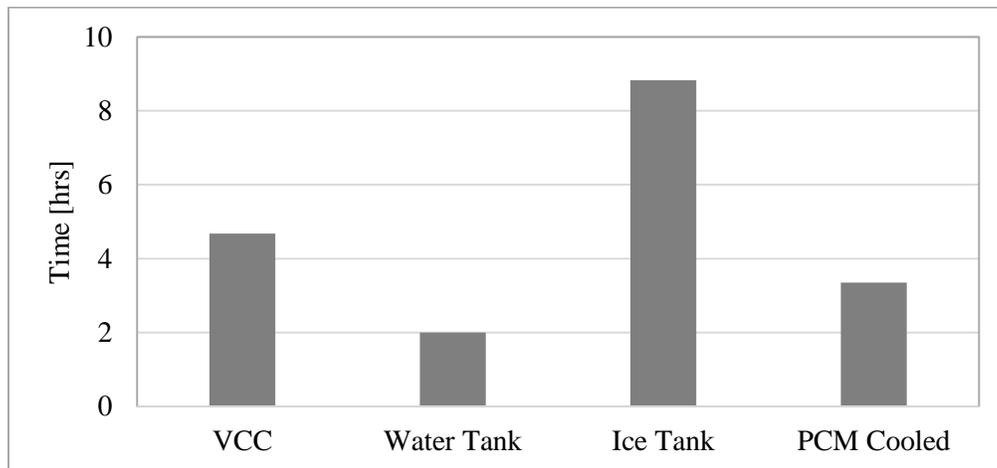


Figure 8: Operation time of a 30-kg system developed from each concept

3. ELECTRODYNAMICS MODELING

The lithium ion battery is modeled as an equivalent resistance and capacitor circuit as detailed in the works of Einhorn (2011) and Muenzel (2015). The values for the constants for the cell used are obtained experimentally using Electrochemical Impedance Spectroscopy (EIS). To obtain the performance of the battery pack from the model of single cell, the boundary conditions are applied to the cell model as if it is located inside the battery pack. The battery pack consists of 21 cells of Samsung ICR 18650 26F, with three parallel circuits of seven cells in series. The model is simulated for the condition of a constant draw of 70 W power. For experimental validation, a 70 W fan is powered by the battery pack and its voltage vs time behavior is recorded. Validation results are shown in Figure 9.

For a typical cycle of RoCo operating for 2 hours with 20 minutes of mobility of the platform, a sample duty cycle is conceptualized and battery consumption noted. In case of VCC, compressor ON-OFF time is 6 minutes ON and 24 minutes OFF. For the water based concepts, the pump is kept running at all times. For the end of first cooling mode of operation, the battery level as per the simulation is shown in Figure 10. It can be observed that all the concepts consume similar amount of power for operation. However, the VCC concept further uses battery for thermosiphon operation. Among the water cycle concepts based on the pumping requirements, the power consumption decreases in the order PCM Cooled, Water Tank and Ice Tank concept. The recharging operation for the other modes does not consume any battery since they are carried out separately.

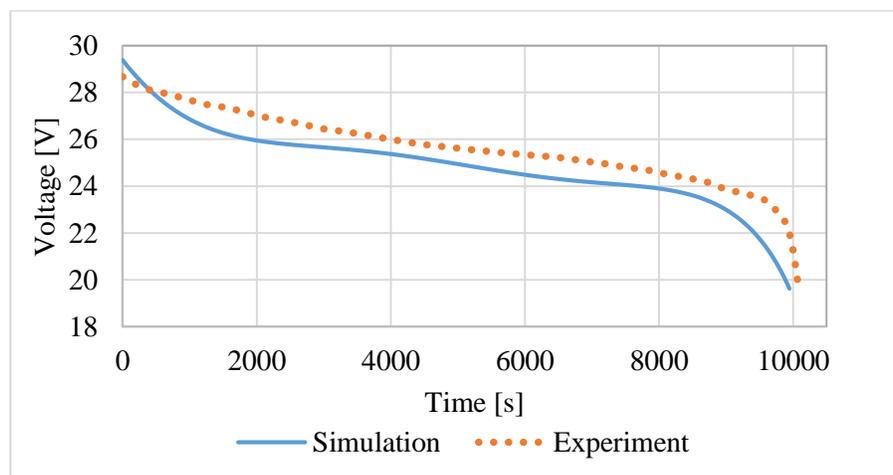
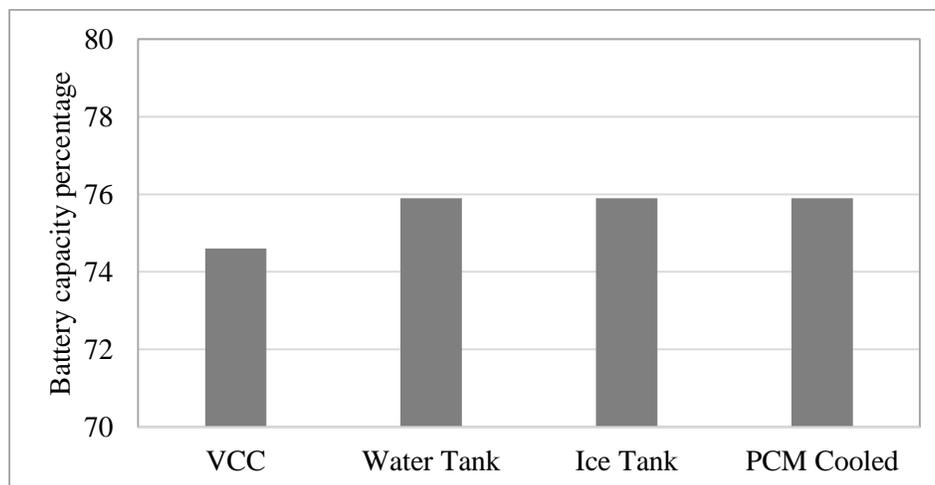


Figure 9: Validation of battery model

Table 1: Power Consumption for Various RoCo Components

Component	Power Consumption [W]
Compressor	55
Fan	4
Controller	2
Robotic Platform	51
Water Pump	4

**Figure 10:** Battery consumption after 2-hour cooling operation

4. COST CONSIDERATIONS

A comprehensive component database has been developed to systematically reduce the manufacturing cost of RoCo. The task is carried out in Microsoft Excel and is a good tool to quickly make an assembly of components that make up the system and analyze its weight and cost. The estimation of bulk cost of manufacturing is a challenge since most of the components like the compressor for the current requirement are not manufactured in large amounts. Since RoCo is a disruptive market product, the exact cost will be available only after it has been manufactured in large quantities. However, by making some reasonable estimates and drawing parallels on reduction of prices, some very good estimates can be done. Figure 11 shows one such attempt at comparing prices of making RoCo with each of these four concepts.

The comprehensive material database is a very good tool to reduce the price of each prototype by providing good visual representation of targets for cost reduction. For the VCC concept, cost reduction is shown in Figure 12. The first prototype which is assembled using the available components is represented by V1. With low cost components developed by the team, the cost shown in V2 is achieved. Further progress in cost reduction is expected for the year end model Y1.

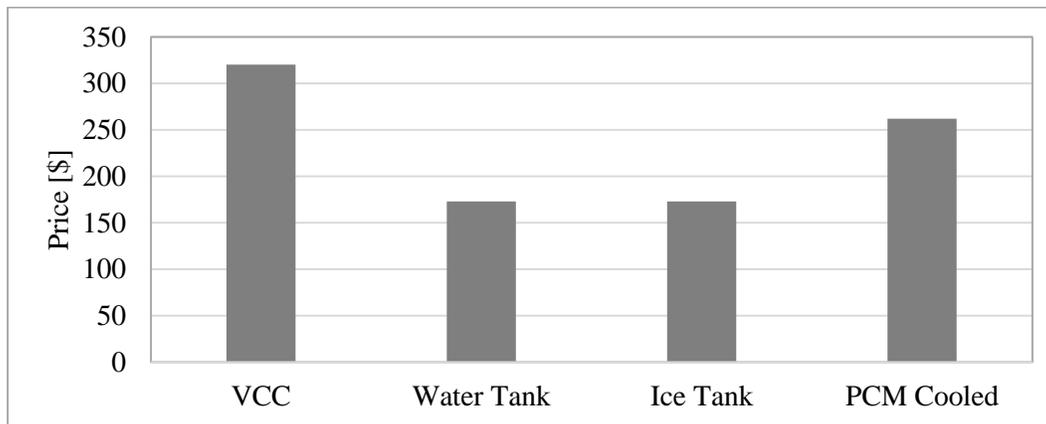


Figure 11: Bulk price of manufacturing RoCo with each of these concepts

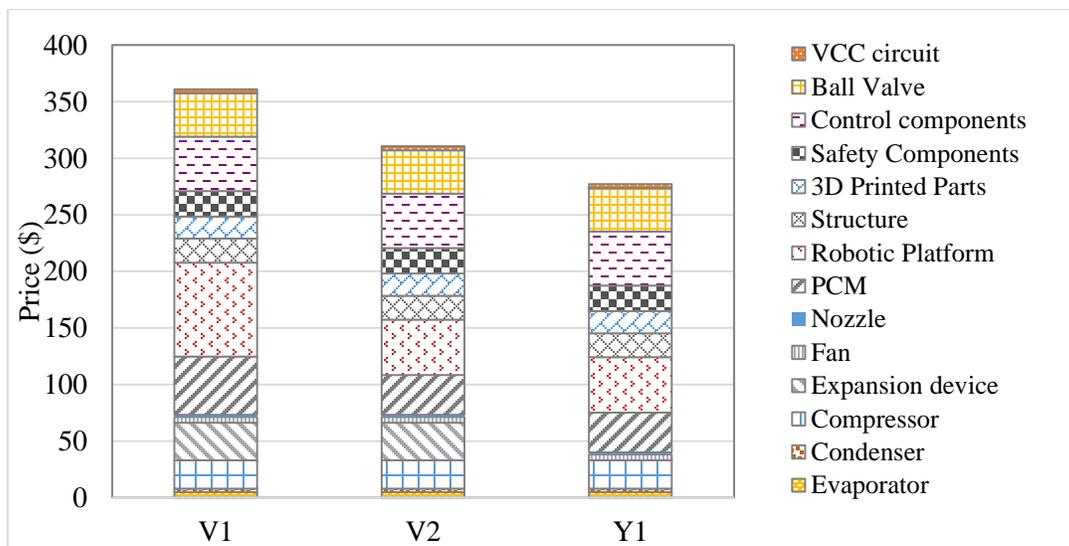


Figure 12: Progressive cost reduction for VCC concept

5. CONCLUSIONS

Four concepts for delivering cooling for RoCo are compared for cost, weight, electrical power consumption and cooling performance. For compactness, ice tank concept ranks the highest, followed by VCC, PCM Cooled and then Water Tank concept in order. VCC and Water Tank concept have higher COP than Ice Tank or PCM Cooled concept because of the temperature range of operation of thermodynamic cycles. Ice Tank and PCM Cooled require temperatures below or near freezing temperature of water. VCC based concept can operate as a standalone with thermosiphon mode for recharging its thermal storage. Ice Tank concept requires higher user interaction in that a person needs to replace ice regularly, making it undesirable. All the concepts consume similar battery power for their operation. In the costing part, VCC concept requires larger cost but that is something that can be reduced. By weighing all the pros and cons, VCC concept has been decided as the most favorable to go ahead with. A prototype for the same has been developed and successfully tested.

NOMENCLATURE

A	Heat Transfer Area	(m ²)
c	Specific heat capacity	(J/kg-K)

E	Energy	(J)
h	Specific Enthalpy	(J/kg)
m	Mass	(kg)
n	Number of ice cubes	(-)
r	Radius	(m)
ρ	Density	(kg/m ³)
T	Temperature	(K)
t	Time	(s)
U	Coefficient of heat transfer	(W/m ² -K)

Subscript

f	Fusion (melting)	s	Solid
ice	Ice	st	Stored
in	Inlet	tube	Refrigerant tube
l	Liquid	v	Constant volume
out	Outlet	w	Water
p	Constant pressure		

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