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CRADA Final Report: CRADA Number NFE-17-06866 with Active Energy Systems, Inc.

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1. Abstract

Cooperative Research and Development Agreement (CRADA) NFE-17-06866 between Oak Ridge National Laboratory (ORNL) and Active Energy Systems Inc. (AES) focused on studying and modeling a low cost, high efficiency energy storage technology. The successful development of low-cost, high-efficiency energy storage is a significant bottleneck in the implementation of intermittent renewable energy sources such as wind and solar. AES is a startup company developing a heat exchange technology to utilize a low-temperature phase change material (PCM). The work done under this CRADA explored this technology's ability to augment a heat pump/heat engine device to convert electricity into thermal energy and vice versa, operating to complement the needs of the electric grid. Modeling, design and development of a prototype to prove the technology was successful, but current production economics and market demand make further exploration undesirable.

2. Statement of Objectives

The three objectives of the CRADA, and their relevant tasks:

1. Active Energy Storage process technical feasibility study

A computer model was needed to verify the technical feasibility of the proposed process. This model would need to be robust to test the operating conditions under a wide variety of input conditions. The accomplishments included the following.

- 1.1 Determining the input parameters and flow diagrams (AES)
- 1.2 Developing the computer model (AES & ORNL)
- 1.3 Understanding the thermodynamic performance sensitivity of each Rankine cycle configuration to input parameters (AES)
- 1.4 Using the computer model to conceptually design the full system prototype (AES & ORNL)

2. Fabricate and test low-cost PCM heat exchanger

A low-cost heat exchanger capable of both freezing and melting the phase change material was necessary for the technology to work. A holistic approach considered the phase change material, heat exchanger material and surface, and physical configuration of the heat exchanger. The piecemeal approach included the following.

- 2.1 Identify materials to limit thermal resistance between the working fluid and PCM (AES)
- 2.2 Computer aided design and bench-scale prototype of a low-cost heat exchanger (AES)
- 2.3 Test a prototype heat exchanger (Target: limit supercooling to 4 °C and achieving a 1 kW/m^2-K overall heat transfer coefficient) (AES & ORNL)
- 2.4 Fabricate a large scale heat exchanger to be used in the full system prototype (AES & ORNL at the advanced manufacturing facilities)

2.5 Address any design or material issues with the prototype [if necessary]

3. **Prototype of proposed concept**

From Task 1, the computer simulation results need to be validated with an experimental prototype to demonstrate commercial viability. The transient start-up, shut-down, and storage behavior of the prototype are intended to complement the steady state information provided by Task 1. In addition to the low temperature heat exchanger developed in Task 2, this prototype will utilize many off-the-shelf components in order to establish the technology readiness level.

3.1 Build the prototype from Task 1.4 (AES & ORNL)
3.2 Comparison of the performance of the prototype against computer simulations (AES)
3.3 Estimate the cost for a pilot scale system (approximately 100 kW_e and 6 hours of storage) on a $/$kWh_e$ and $/$kW_e$ basis (AES & ORNL)

3. Benefits to the Funding DOE Office's Mission

Hardware-based technological innovations in the energy market are difficult to realize with low-level waste heat due to high capital costs and stringent validation requirements. Collaboration with the Building Technologies Research and Integration Center (BTRIC) at ORNL helped analyze and address these issues. The expertise by BTRIC in collaborating with industry proved invaluable for AES in navigating industrial standards and the scaling up of icephobic heat exchange (IHEX) technology, especially to address the development of a system for pumped thermal energy storage. In return, IHEX technology has the potential to assist BTRIC in its mission to integrate building HVAC with the grid.

4. Technical Discussion of Work Performed by All Parties

This is a report based on the work performed in the aforementioned task list. Results from Task 1 are planned to be published under the working title: "A virtual analysis of pumped thermal electricity storage – a model-based performance evaluation of isothermal cold-thermal energy storage and its improvement over conventional sensible heat designs" by Peter M. Miklavcic, Kyle R. Gluesenkamp, and Mitchell Ishmael.

The first half of Task 1.1 involved designing a flow diagram for the technology. A design would require a way of turning electricity into thermal energy and storing it, and later retrieving that stored energy and reconverting it to electricity upon demand. The final layout consisted of one circuit with a heat pump (HP) and a heat engine (HE) as two subsystems, shown below in Figure 1.

The first sub-circuit focusses upon storing thermal energy in the PCM with an electrically driven vapor compression heat pump. In steady state operation, the cold working fluid begins at stage 1 in the evaporator. Heat is removed from the phase change material by the working fluid, which is subsequently stored as thermal energy. Next, the working fluid is compressed to elevate the pressure and temperature. Next, the condenser allows the compressed working fluid to discard waste heat into the atmosphere. The working fluid is cooled further and decompressed in the following subcooler and expansion valve, returning a cool uncompressed working fluid to the evaporator at stage one. This completed circuit allows for the continuous storing of cooling of the thermal storage, storing the cold thermal energy.

Known as a heat-engine, the second sub-circuit is the reverse of the first sub circuit and allows for the transformation of stored thermal energy into electricity. The working fluid now uses the stored cold as a condenser and can release the stored cold thermal energy back into electricity.

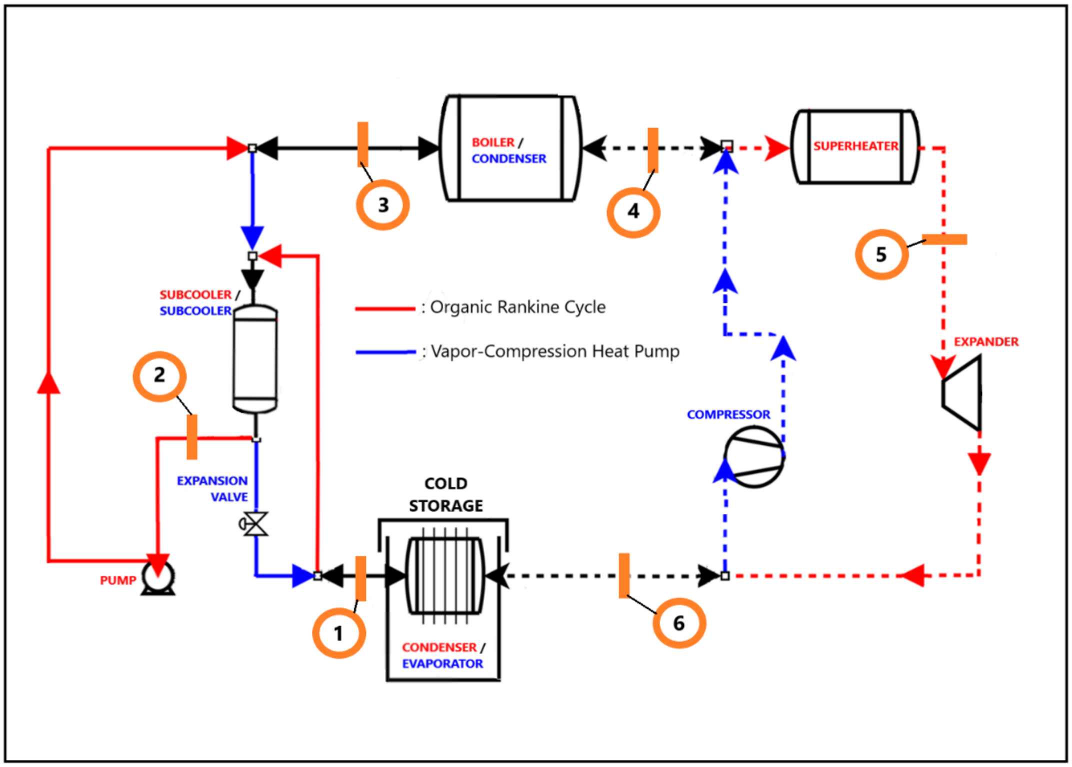


Figure 1: A diagram of the HP-HE circuit, split into the two sub-circuits.

The second half of task 1.1 included in-depth research of the various realistic inputs for the model. The model was designed so that a stratified glycol system could be compared to the proprietary icephobic heat exchanger (IHEX) technology developed by AES. Another example consideration was the efficiency of the various components. For example, while ideally compressors would be isentropic, in the real world they are not due to electrical and mechanical inefficiencies.

Task 1.2 involved making a robust computer model to simulate the previous design. This was achieved with a model written in MATLAB R2018a. This model interfaced with the CoolProp database of working fluids thermodynamics. Task 1.3 involved iterating the model through a variety of design and operating conditions. Parametric studies were accomplished focusing on one or two independent variables. The model was then used for modelling the designed experimental prototype in Task 1.4. The results of this model are being organized for publishing in the aforementioned article.

The work done in Task 2 focused upon joining AES's proprietary IHEX technology to a designed prototype test rig. Utilizing a thin fluoropolymer to achieve efficient heat transfer while maintaining icephobicity allowed for the successful completion of Task 2.1. The small scale design and testing of IHEX, Task 2.2, was successfully completed next. Figure 2a has an image one of the small scale prototypes. During Task 2.3 heat transfer coefficients greater than 0.8 kW/m^2-K were achieved with scaled up heat exchangers, but the target coefficient of 1 kW/m^2-K requires further developments of the IHEX technology. The finalized design can be seen below in Figure 2b. Tasks 2.4 and 2.5 were also satisfactorily completed, with an appropriate heat exchanger to be mounted within the IHEX being designed and created.

Figures 2a and 2b: (left) A benchtop prototype heat exchanger, and (right) the final constructed prototype rig.

Tasks 3.1 took longer than anticipated. Attention to safety was a priority throughout the design and build phases, so external expertise was often used to ensure safe design and quality work. Numerous experts were consulted to design, build, and validate various pieces of the equipment. Example of expert design and construction are the frame (Bertelkamp Automation, Inc.), the hundreds of feet of high pressure copper tube (ORNL), and significant electrical infrastructure (ORNL). AES consulted with members of the academia from Purdue University and the University of Liege in Belgium. Industrial standards were followed when applicable. The copper lines for example followed the appropriate ASTM and ASME guidelines. Since failure of any of these pieces could potentially result in damage to equipment and personnel, safety procedures were taken with due seriousness. Even with the high quality work, issues were found. For example, leaks within the copper tubing required extensive work to fix to prevent refrigerant leakage. In depth procedures and a HAZOP verified by systems safety analysts were developed for future use of the prototype.

Completion of Task 3.3 resulted in estimates of power cost ($2000/kW) and energy storage costs ($35/kWh). Costs were calculated using material costs derived from the prototype design, and operating costs from the modeling results. The DOE's 2019 "Energy storage technology and cost characterization report" estimates the 2025 Lithium-ion battery storage costs at $362/kWh. While the normalized energy storage costs are attractive compared to projections of Li-ion battery costs, the normalized power costs remain prohibitively expensive. Low energy storage costs and high power costs make this technology well suited for long-duration energy storage (days to weeks of storage), but the market outlook for long-duration storage appears to be poor for the next five years. The results of this economic and market analysis led AES to conclude that pursuing this particular application of IHEX technology was not warranted.

5. Subject Inventions (As defined in the CRADA)

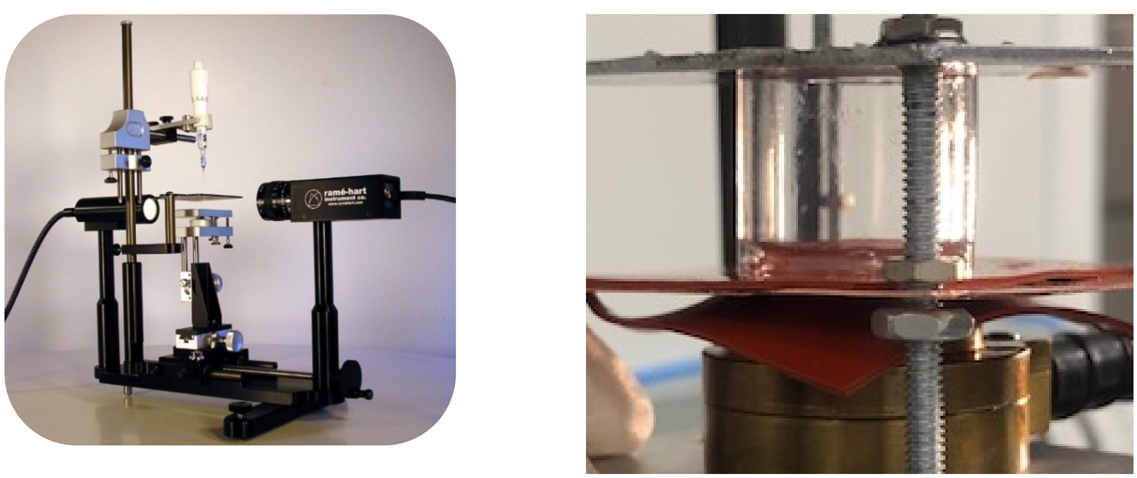
None.

6. Commercialization Possibilities

The results from the computer simulations demonstrated high round-trip electrical efficiencies of 81.6% were possible by utilizing the AES IHEX design for pumped thermal energy storage. This was in comparison to efficiencies of only 60.5% in a stratified glycol system. Even with these large gains, energy market trends indicate that utilizing pumped thermal energy storage is not likely to be economical over the next five years. As a result, AES has decided to focus on using IHEX technology for thermal energy storage for building and process cooling.

7. Plans for Future Collaboration

Further research into surface modification of the IHEX could potentially yield the improvements to the heat transfer rate and ice nucleation properties of the heat exchanger surface (mentioned in the discussion of Task 2.3). Therefore, a research plan for collaboration with the Center for Nanophase Material Science at ORNL has been developed. Utilizing the available goniometers (Figure 3a) with appropriate modifications (Figure 3b) will allow high resolution surface research.



Figures 3a and 3b: An example goniometer available at CNMS, and an AES designed goniometer rig for measuring ice nucleation events and ice adhesion.

AES plans to continue collaborations with the Building Equipment Research Group at ORNL as the company continues to explore thermal energy storage applications for building cooling.

8. Conclusions

During this CRADA, a robust model of the pumped thermal energy storage system was developed. The IHEX technology developed by AES was successfully scaled up and mated to a large prototype system. The completed economic analysis of IHEX for pumped thermal energy storage helped AES conclude that this technology is currently not economically feasible. AES intends to continue developing the IHEX and continue collaboration with ORNL for thermal storage applications