A Comprehensive Mechanical Engineering Perspective on the Implementation of an Organic Rankine Cycle for Data Center Waste Heat Recovery

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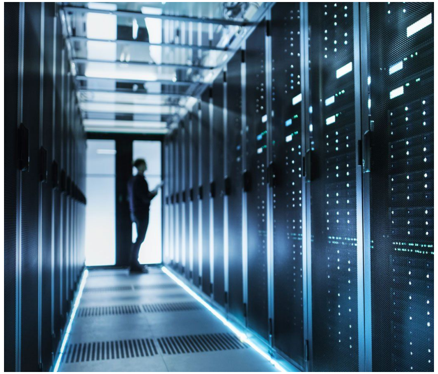
Problem: IT equipment in data centers currently consume exorbitant amounts of energy due to cooling

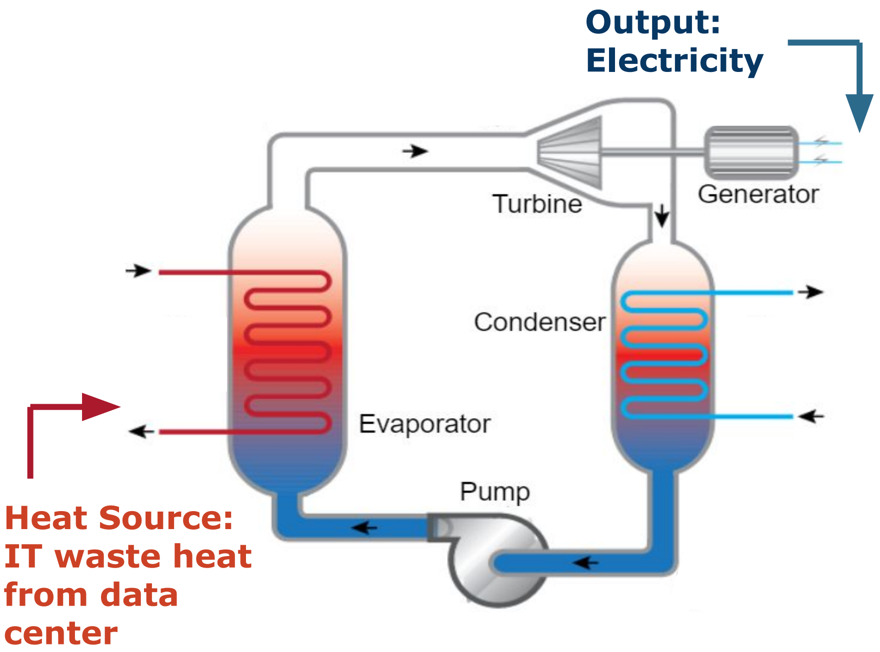


50% Electricity for Power

50% Electricity for Cooling

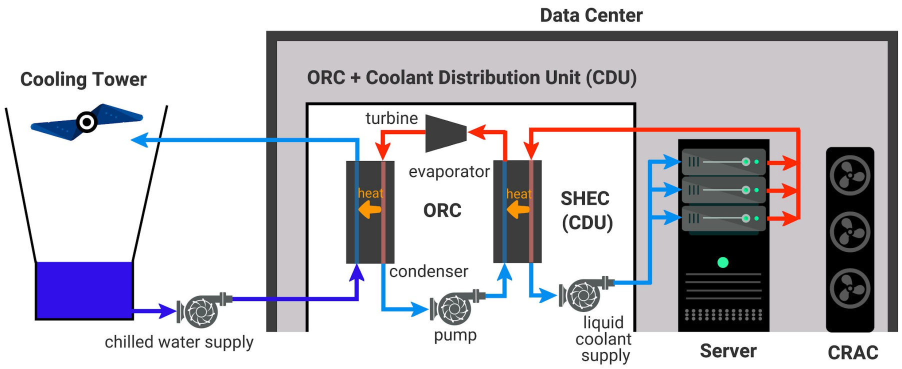
- **Data centers** host large groups of networked servers used for data processing, storage, and distribution.
    - Data centers are responsible for 2% of electricity consumption in the US (half of which is for cooling).
- Advancement of computer technologies has resulted in a dramatic growth in this industry; predicted increases in annual power demands are as high as 15-20%.
    - Hyperscale data center growth is also occurring at an increasing rate, especially in the US.
- **The development and implementation of waste heat recovery systems in data centers has the potential to change the trajectory of data center energy consumption.**

Solution: Organic Rankine cycles have emerged as the leading technology for low-quality waste heat recovery



- **Organic Rankine cycles (ORCs)** are the most promising system for low-quality (low temperature) waste heat recovery in data center applications.
- ORCs are reliable, effective, and can achieve thermal efficiencies close to the ideal maximum of the system.
- Most notably, ORCs **reduce energy demands for cooling while producing a electricity for the data center, essentially from a free by-product of IT equipment: heat.**
- The electricity generated by the ORC thermodynamic processes then provide a source of revenue in the form of offsetting electricity costs.

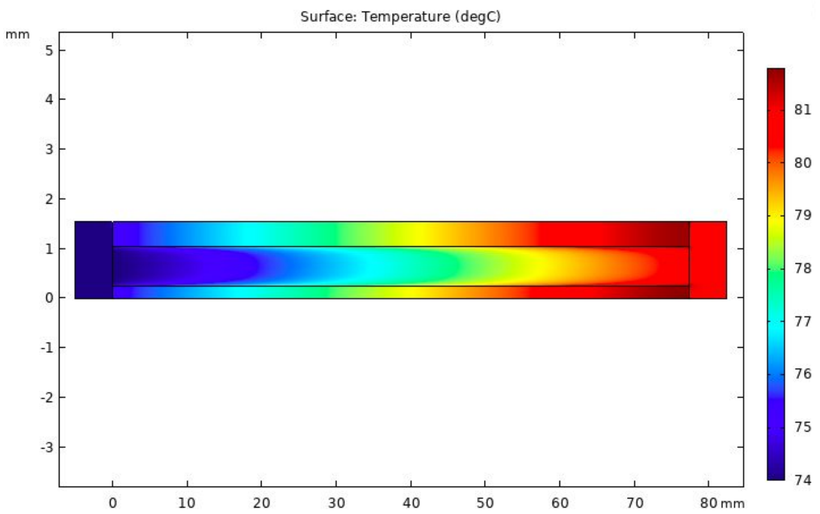
Implementation: The optimal means for cooling IT equipment and transferring waste heat to the ORC is a liquid cooling system



- For many years, **air cooling** has been the dominant form of data center cooling, which involves the use of rack-level or server-level fans to force air over the IT equipment, removing heat from the components via convective heat transfer.
- **liquid cooling** has become more prevalent in new-age, high density data centers, which require the removal of much higher heat fluxes.

- In liquid cooling, a fluid is pumped from a coolant distribution unit (CDU) to the enclosed heat sinks mounted on the heat generating components within a server. In a traditional data center, the coolant dissipates heat from the IT equipment, is circulated back to the CDU where it is cooled, and then returns to the servers to repeat the cycle. However, **in this project, the coolant distribution loop was reimagined as a server heat extraction cycle** (SHEC) wherein the heat extracted from the IT equipment was used as the heat source for an ORC to generate electricity.

Simulation: The feasibility and effectiveness of a liquid cooling SHEC was verified via thermal and fluid FEM

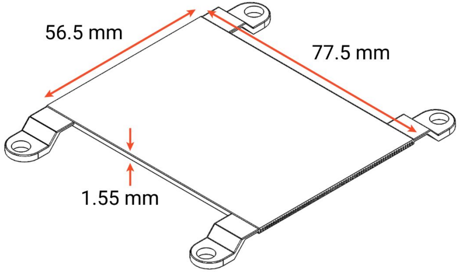


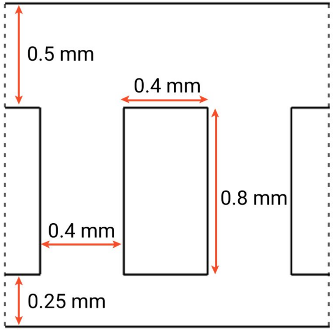
2D temperature plot (℃) along a mid-channel slice with water (horizontal axis scaled 0.15)

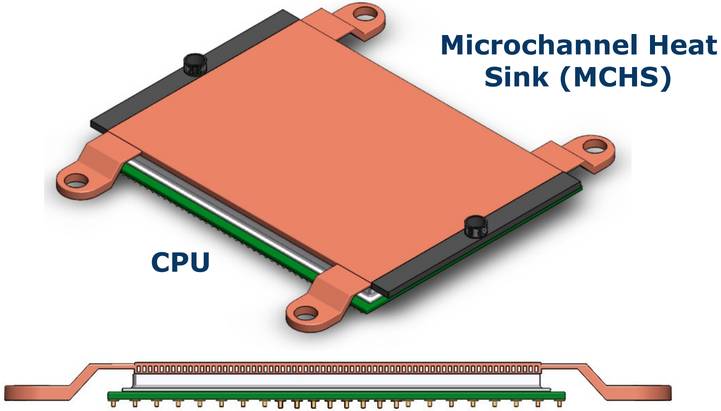
- Since ORCs are an emerging technology for data center waste heat recovery, prior research has been limited to theoretical and experimental thermodynamic analyses under expected operating conditions from data center applications.
- **This project aimed to directly address how heat would be extracted from the IT equipment** (specifically the CPU) and transferred to the ORC evaporator.
- To investigate the fluid and thermal interactions between the coolant and the chip, a section of a microchannel heat sink was evaluated in the simulation software, COMSOL, which was used to perform finite element analyses.

Simulation: The feasibility and effectiveness of a liquid cooling SHEC was verified via thermal and fluid FEM

- A range of fluids, flow conditions, and heat sink geometries were tested to determine which model and set of operating conditions ensured adequate cooling of the CPU and maximized the amount of heat that could be utilized by the ORC.
- We found that **single-phase, laminar flow of liquid water** provided the highest temperature profiles while minimizing pressure drop and maintaining safe operating temperatures under 85°C.
- The results from the simulation were then used in subsequent calculations to **precisely characterize the waste heat recovery system**.



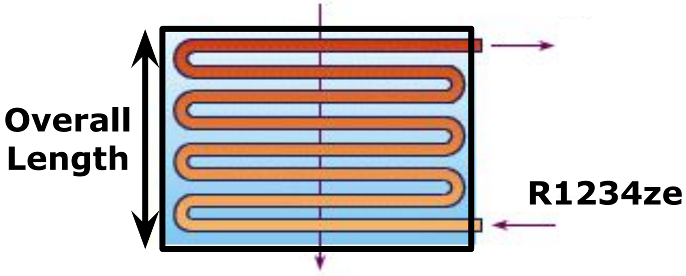




ORC Mechanical Design: Modeling internal axial fins within a shell and tube heat exchanger produced practical designs for the ORC heat exchangers

Shell & Tube Schematic for ORC Heat Exchangers

Water (servers) - evaporator or Water (coolant) - condenser

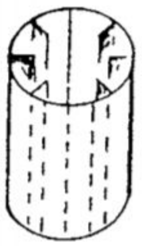


***N* tube passes**

- Another major aspect regarding the implementation of ORCs for waste heat recovery in data centers is the **mechanical feasibility of the system**, which has not yet been addressed in literature.
- The heat exchangers are essential features of the ORC and must perform sufficiently within the narrow range of data center waste heat temperatures.
- Furthermore, we wanted to design an ORC that implemented **R1234ze**, a working fluid that is an **environmentally-conscious alternative** to conventional refrigerants with high Global Warming Potentials.

ORC Mechanical Design: Modeling internal axial fins within a shell and tube heat exchanger produced practical designs for the ORC heat exchangers

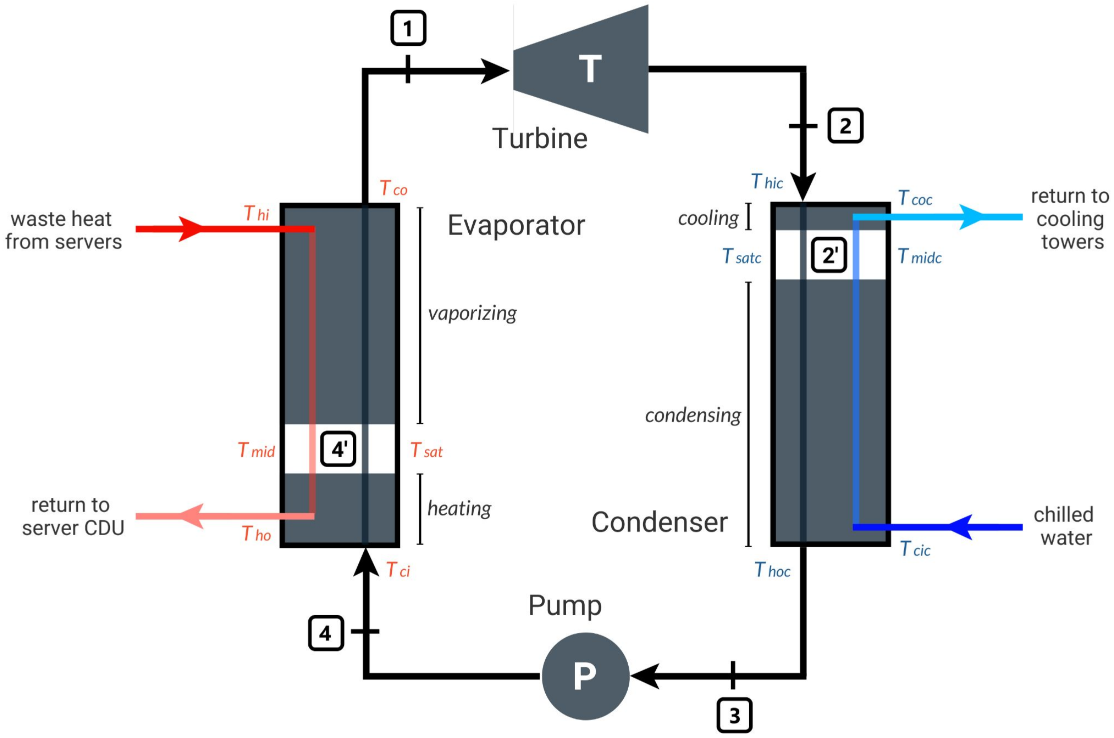
- To assess the viability of the physical ORC system under the unique conditions, an extensive **heat exchanger design analysis** was conducted for a given 10 kW heat load (corresponding to the load of the server room in Atwater Kent Laboratories at WPI).
- The most conservative evaporator design was a shell and tube heat exchanger, **0.76 m** in overall length, with **50 tube passes** of a single pipe.
- The most conservative condenser design was a shell and tube heat exchanger, **0.35 m** in overall length, with **20 tube passes** of a single pipe.
- Both heat exchangers utilized nominal ⅜ inch tubes with an additional design feature of **internal axial fins**.



Internal Axial Fins

	Overall Length (m)	Tube Passes	Tube Length (m)
Evaporator	0.762 (30 in)	50	35.45
Condenser	0.305 (12 in)	20	6.08

ORC Thermodynamic & Fluid Analysis: The final design of the proposed ORC performed successfully, and within the performance range provided in literature



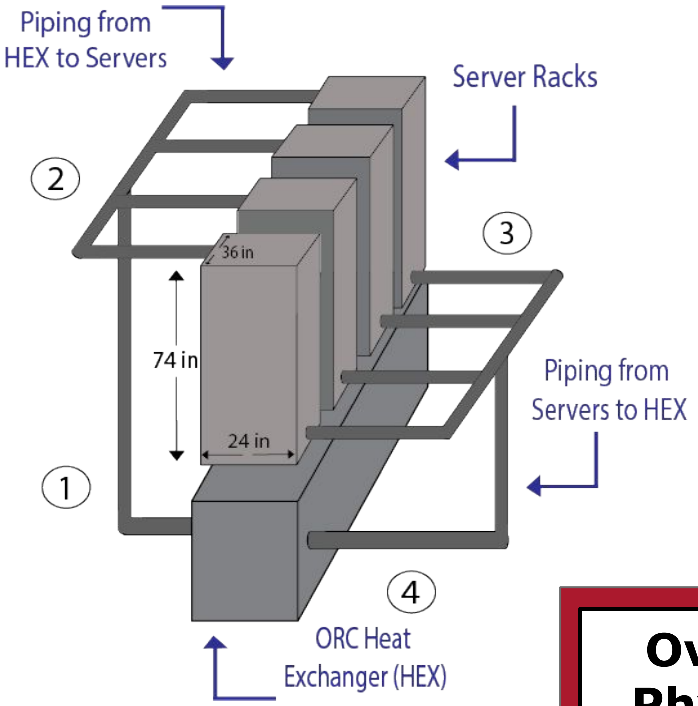
- The thermodynamics and fluid mechanics of the ORC were also addressed by developing a **robust representation of the system in MATLAB**.
- The program was used to integrate the heat exchanger, thermodynamic, and fluid mechanics analyses to precisely determine the efficiencies, power outputs and inputs, and pressure drops over the ORC connecting pipes.

ORC Thermodynamic & Fluid Analysis: The final design of the proposed ORC performed successfully, and within the performance range provided in literature

- Based on the results from the CPU heatsink simulations and thermal performance of the heat exchangers, the ORC for the **10 kW heat load** produced an efficiency of **4.46 %**, within the typical range of **2% - 8%** reported in literature.
- The **net power output** of the ORC system was **436 W**.

Carnot Efficiency (maximum efficiency)	6.42%
Thermal Efficiency	4.46%
Turbine Power (W)	491
ORC Pump Power (W)	55.4
ORC Net Power Output (W)	436

SHEC Design & Fluid Analysis: The final design of the SHEC piping system minimized the required pump power

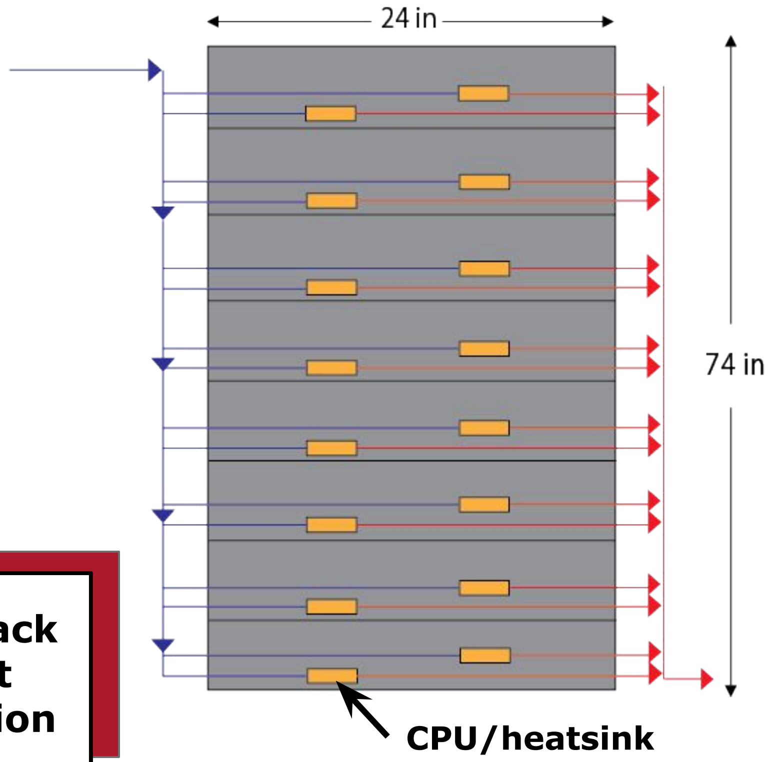


Overall Physical Layout

- The last remaining aspect of the waste heat recovery system that has not yet been explored in literature is the **mechanical design of the liquid cooling system**, which is used to transport heat from the IT equipment to the ORC.
- we developed a generalized configuration for the overall layout and piping manifold for the SHEC.
- the ORC system was located below the floor of the server room, wherein water is pumped up to the top of the server racks, distributed to the CPUs and heatsinks, recollected at the base of the racks, and finally pumped back down to the ORC heat exchanger.

SHEC Design & Fluid Analysis: The final design of the SHEC piping system minimized the required pump power

- The dimensions for the piping system were approximated, since we intended this generalized configuration would be adjusted for a selected data center.
- We performed a fluid mechanics analysis on the SHEC piping manifold for the **10 kW** heat load scenario, and determined an overall pressure drop of **10.0 kPa**, which corresponded to a pump power of **8.0 W.**



Server Rack Coolant Distribution

Economics: Economic analyses indicated that the proposed ORC heat waste recovery system was both feasible and financially advantageous

	small-scale system		*large-scale system*	
	10 kW (ORC/SHEC)	**10 kW (air cooling)**	**1000 kW (ORC/SHEC)**	**1000 kW (air cooling)**
Capital Cost	-$2,030.83	-$1,466.00	-$203,083.10	-$94,557.00
Life (yrs)	20	6	20	6
Annual Capital Flow (+Revenue/-Cost)	$363.01	-$171.03	$52,603.20	-$11,031.45
Interest Rate	5%	5%	5%	5%
EAC	$200.14	-$459.83	$36,315.93	-$29,659.18
Payback Period (yrs)	6.7	n/a	4.0	n/a

- Both an **equivalent annual analysis** and **discounted payback period** calculation were used to compare the ORC waste heat recovery system with conventional air cooling systems and to assess whether the proposed ORC system was financially viable. In the analysis, two scales corresponding to **10 kW** and **1000 kW** of thermal load from the data center were evaluated.
- The **equivalent annual analysis** shows that over the lifetime of the cooling systems, the ORC system produces an inflow of revenue (due to the electricity produced by the ORC turbine) while the conventional cooling system produces annual costs.

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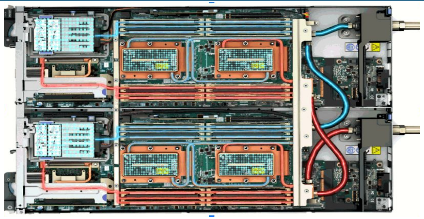
- Regarding payback period, data centers typically have a lifespan of **20 years**, and ORCs have shown to have similar lifetimes. After the short period of **4 to 7 years** required to pay off the cost of the system, the ORC produces revenue for the data center.
- Not only does the ORC waste heat recovery system provide an economic incentive for data center proprietors, but it also significantly reduces the energy demand. The IT equipment is predominantly cooled by the liquid cooling system, which only requires a small power input for the pump. Ultimately, the system that we have proposed **enables data centers to significantly reduce the energy** requirements for cooling, and **provides additional income** to the data center for the majority of its lifetime.

Future Work: From a comprehensive mechanical engineering perspective, the ORC waste heat recovery system is mechanically and financially viable, and sustainable



Liquid cooling with microchannel heat sinks

ORC electricity production from waste heat

Reduce energy consumption & generate revenue from cooling in data centers

- The investigative activities and computational analyses employed in this project have demonstrated that **an organic rankine cycle system can be considered a sustainable solution for recovering data center waste heat**. Since water is used for the server heat extraction cycle, and an environmentally-conscious refrigerant R1234ze is used for the ORC working fluid, the system itself limits its impact on the environment while serving to dramatically decrease energy demands related to data center cooling.
- The success of this comprehensive theoretical analysis is **highly encouraging for future study** in the application of this system. With additional specification and adaptation, **a pilot version** of the theoretical system presented in this project **could be implemented at an existing data center**.

Sources

Images:

- *https://www.trinustech.com/wp-content/uploads/2020/08/cloud-computing.jpg*
- *https://www.lenovo.com/us/en/data-center/servers/racks/ThinkSystem-SR655/p/77XX7SRSR75*
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