Modeling and Simulation of a Thermoelectric Heat Pump with Micro-Channel Heat Transfer, and Applications for Thermoelectric HPs in Buildings

3.11 Non-Traditional Technologies

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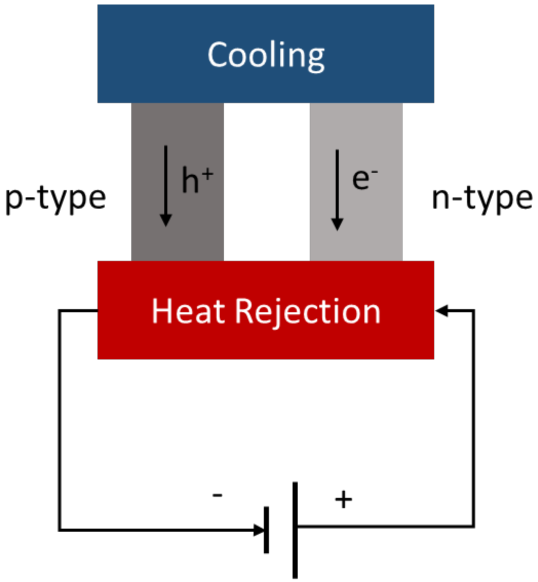
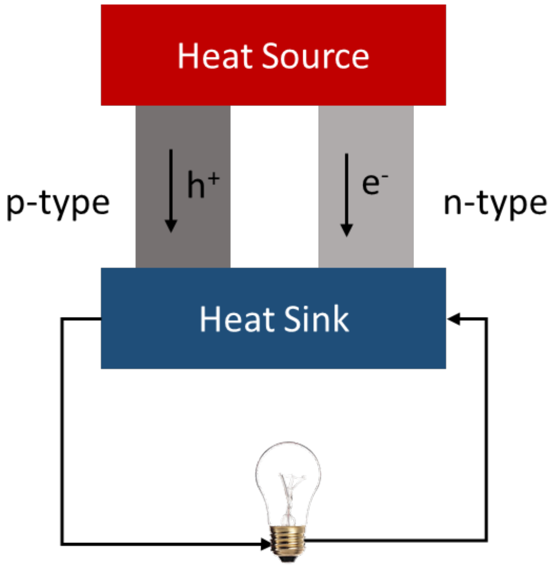
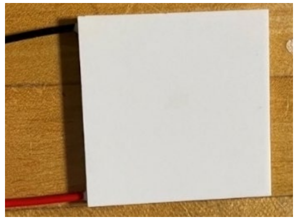
Working Principles

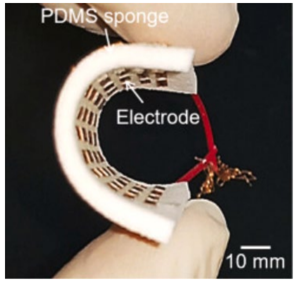
- A thermoelectric (TE) module can work as a cooler or a generator;
- The TE module can be manufactured in different structures.



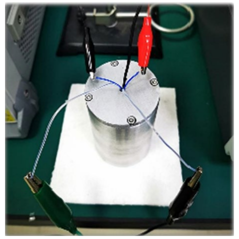




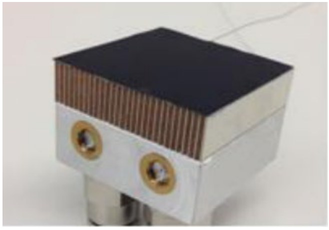
(a)



(b)



(c)



(d)

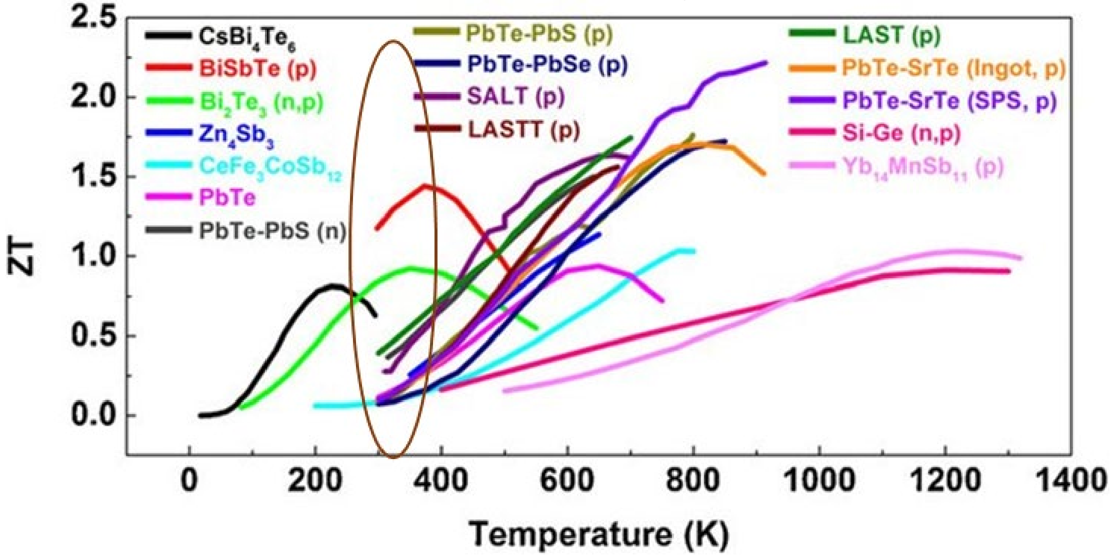
(a) standard π–type geometry (b) flexible array
(c) annular structure (d) stack structure

1. Porous organic filler for high efficiency of flexible thermoelectric generator https://doi.org/10.1016/j.nanoen.2020.105604
2. Experimental optimization of small–scale structure–adjustable radioisotope thermoelectric generators https://doi.org/10.1016/j.apenergy.2020.115907
3. Cost Efficient Manufacturing of Silicide Thermoelectric Materials and Modules using RGS Technique https://doi.org/10.1016/j.matpr.2015.05.074

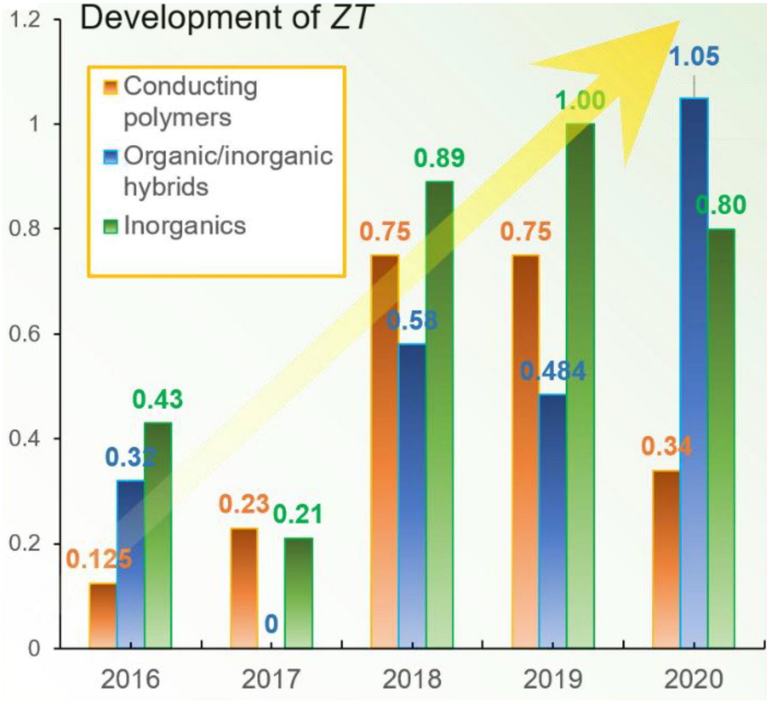
Thermoelectric Materials

- Bismuth telluride (Bi_2Te_3) is the most mature and widespread and works well around room temperature
- Flexible TE (FTE) materials are approaching conventional material
- $ZT = \frac{\alpha^2 T}{\kappa\rho}$

TE material ZT vs. Temperature



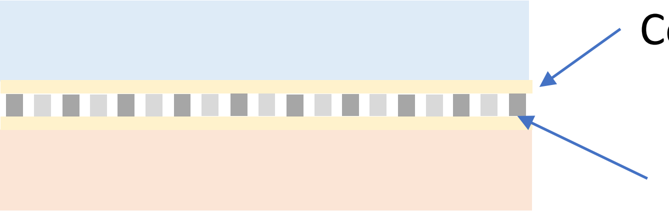
Report ZT for FTE materials between 2016 and 2020



1. He J, Kanatzidis MG, Dravid VP. High performance bulk thermoelectrics via a panoscopic approach. Materials Today 2013;16:166–76. https://doi.org/10.1016/j.mattod.2013.05.004.
2. Zhang L, Shi X-L, Yang Y-L, Chen Z-G. Flexible thermoelectric materials and devices: From materials to applications. Materials Today 2021;46:62–108. https://doi.org/10.1016/j.mattod.2021.02.016.

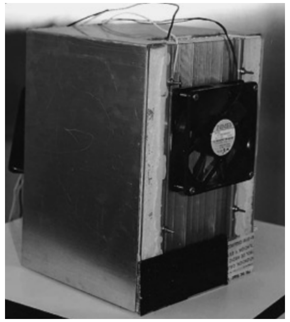
Thermoelectric Heat Pump

- TEHPs are commonly used in a sandwiched configuration;
- They have been applied in multiple locations.



- ORNL team has successfully developed multiple TE-integrated residential appliances – dishwasher, water heater, cloth dryer, etc.

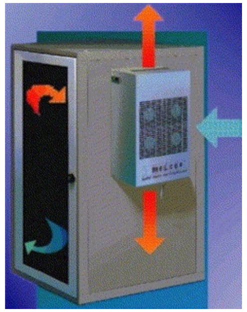
Dehumidifier



Baby incubator

Portable refrigerator

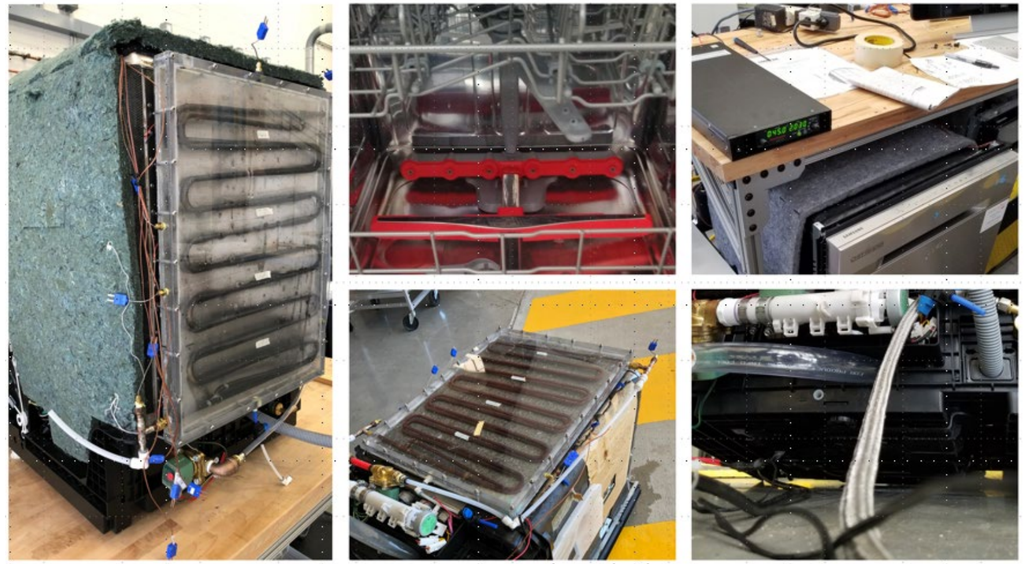
Small AC



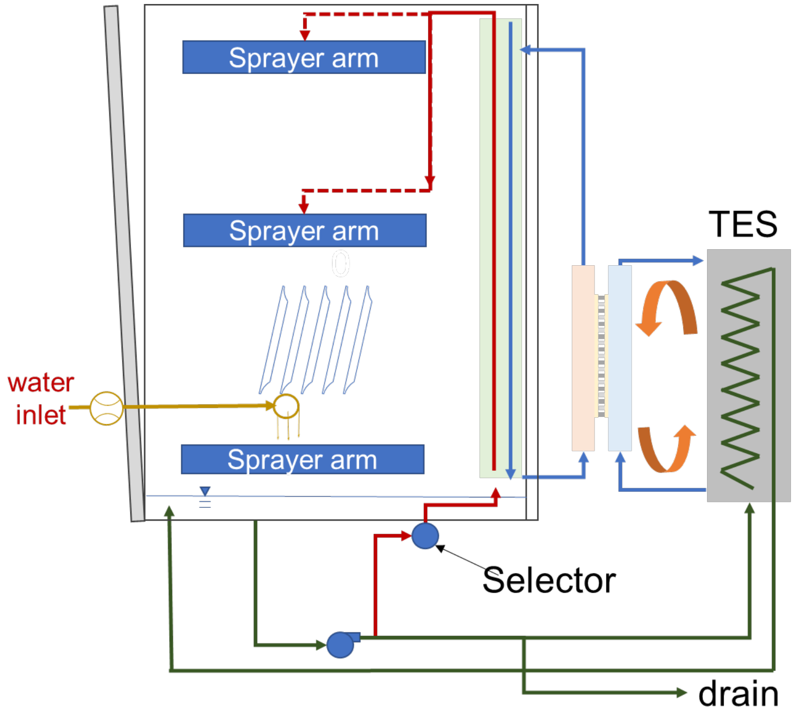
1. Development and applications of thermoelectric based dehumidifiers https://doi.org/10.1016/j.enbuild.2021.111446
2. Performance prediction modeling of a premature baby incubator having modular thermoelectric heat pump system https://doi.org/10.1016/j.applthermaleng
3. https://russalesov.com/product_details/13104660.html
4. Riffat SB, Qiu G. Comparative investigation of thermoelectric air-conditioners versus vapour compression and absorption air-conditioners. Applied Thermal Engineering 2004;24:1979–93.

Thermoelectric Dishwasher

- 30% energy saving for water heating
- 20% improvement in drying performance



Prototypes in the laboratory

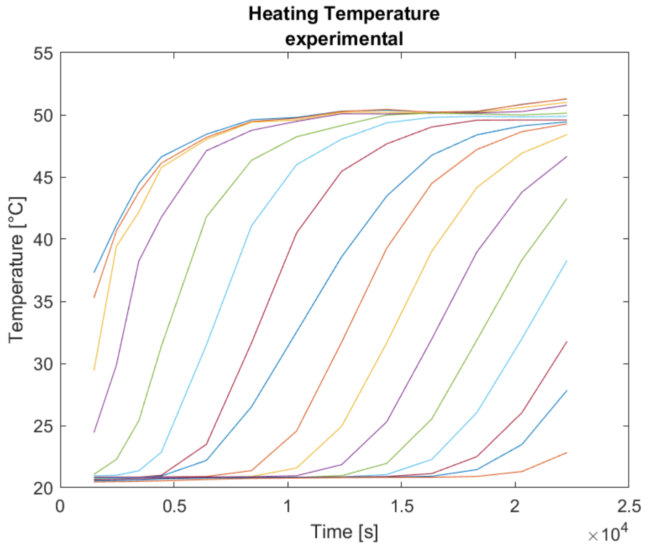


Novel Dishwasher System Configuration

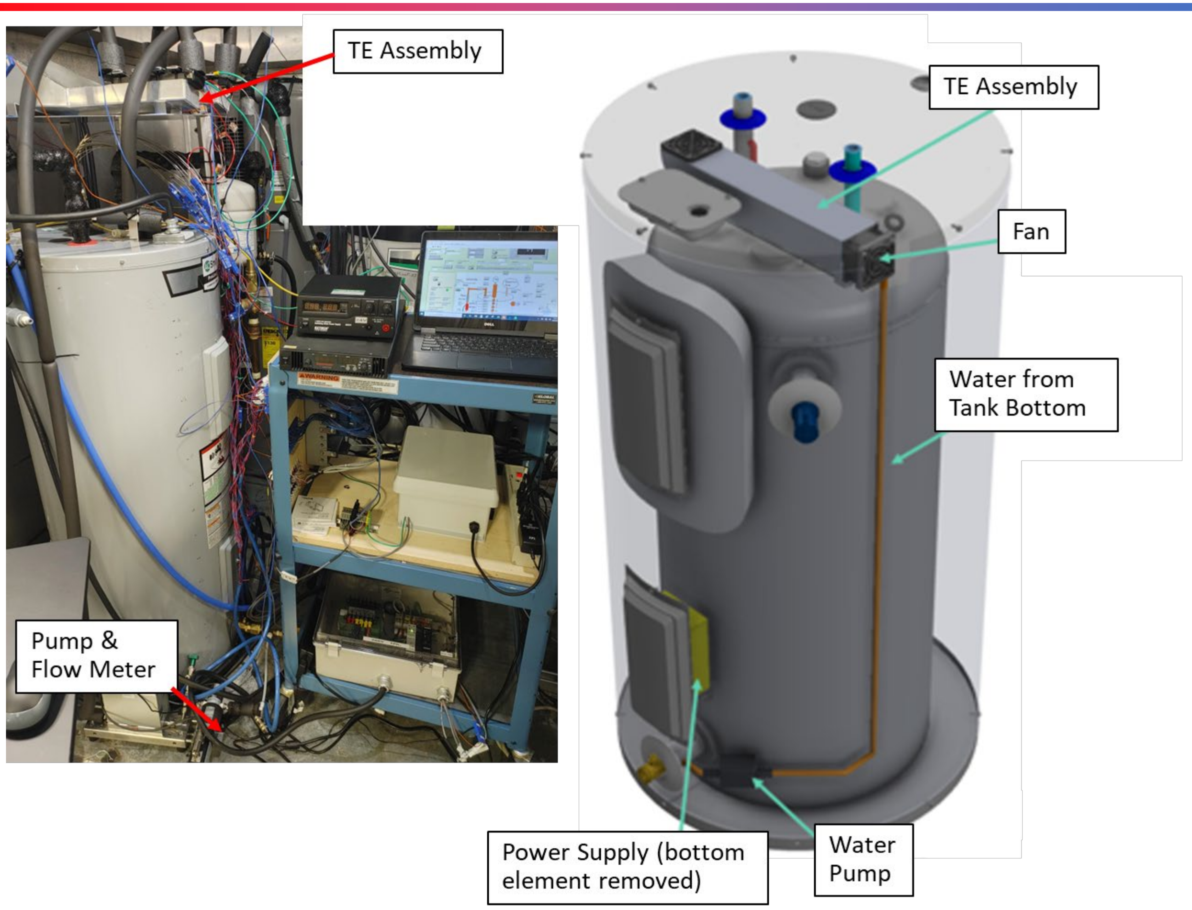
1. Kumar, N., Gluesenkamp, K.R., Rendall, J., Patel, V., Gehl, T., Abu-Heiba, A., Turnaoglu, T., Wu, G. and Vaidhyanathan, R., 2021. Novel Dishwasher with Thermal Storage and Thermoelectric Heat Recovery.

Thermoelectric Water Heater

- TE water heater prototype experimentally nearly completed a UEF with value of of 1.00, better than Resistive Electric (0.95). It had only 585 W maximum heating capacity, but the last draw missed by 1.5°F for 90 s.
- Parasitic power is <5 W for the pump and 23 W for fans, with losses (parasitic & heat) around ~9%.



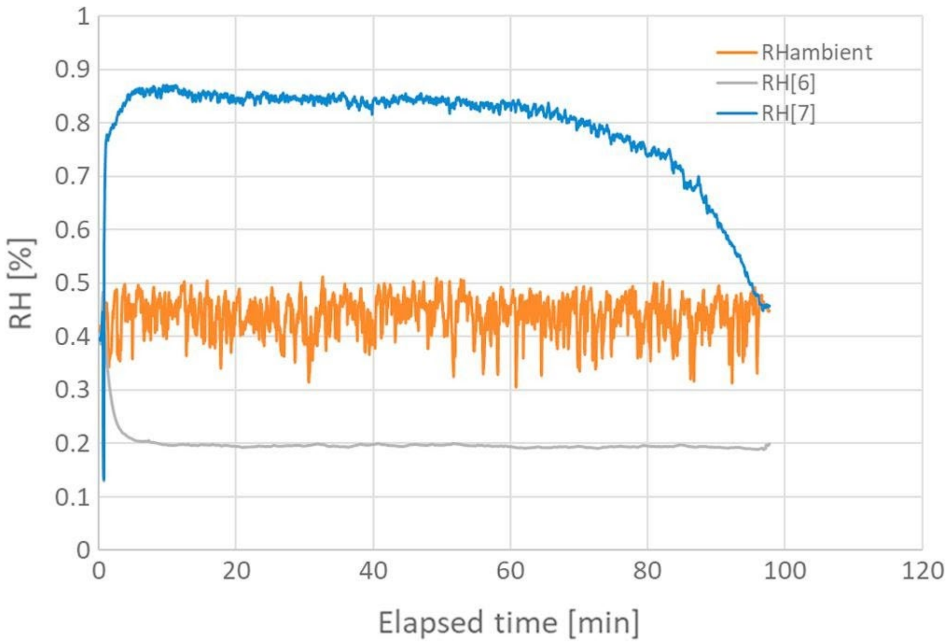
Experimental temperatures in the tank



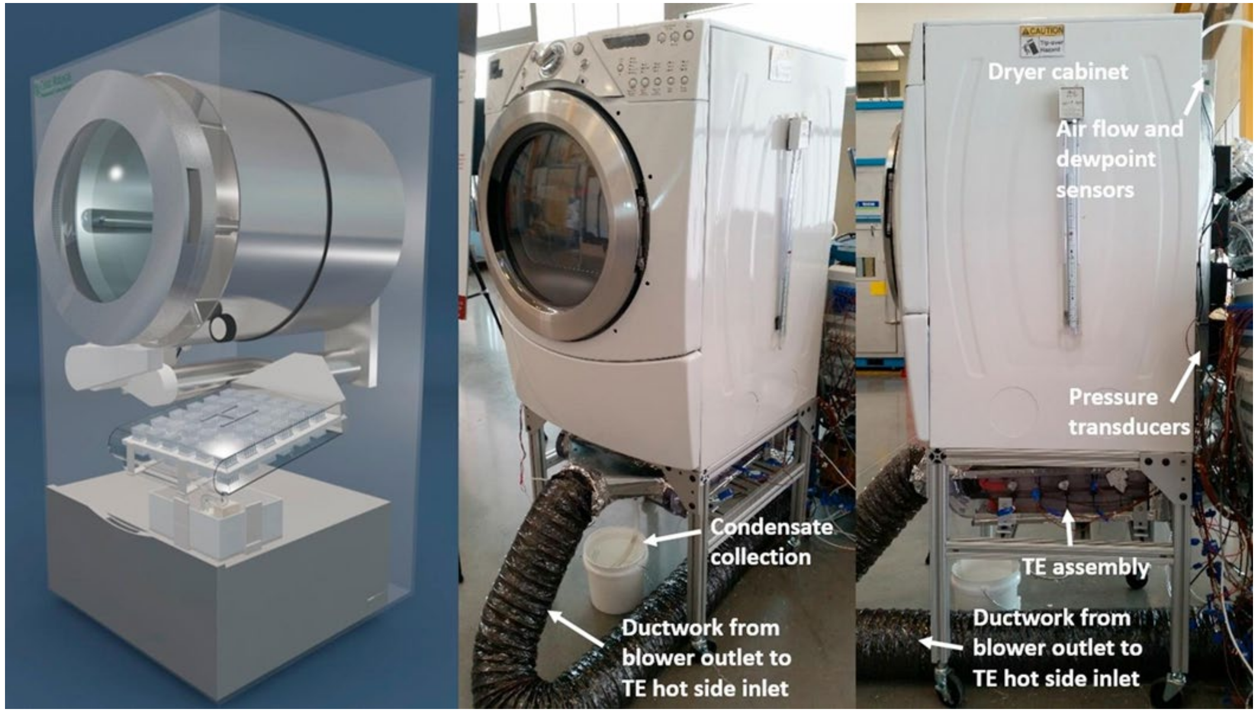
Novel TE HPWH Photo & Configuration

Thermoelectric Clothes Dryer

- Experimental results showed energy factors (EFs) up to 2.95 kg of cloth per kWh with a dry time of 159 min, and a faster dry time of 96 min with an EF of 2.54 kg/kWh



Measured RH values change

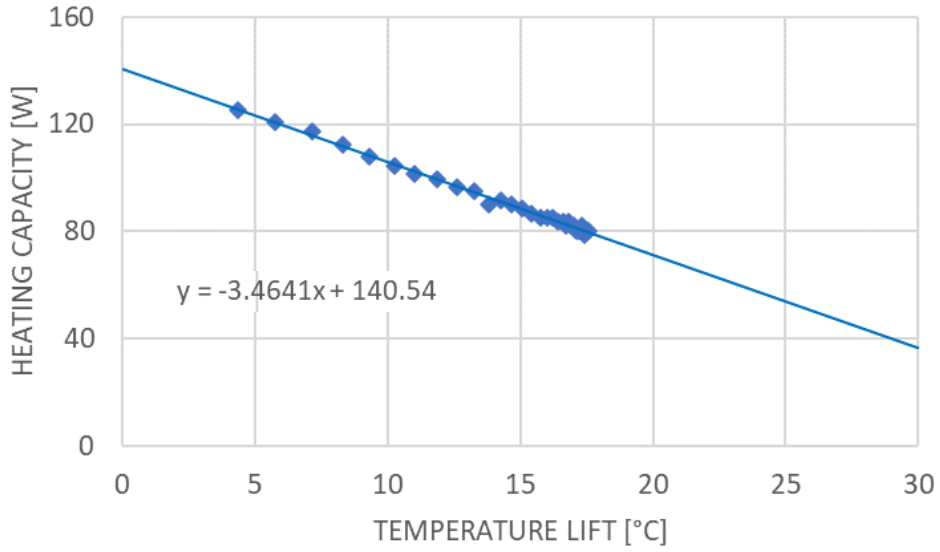


Novel System Photo & Configuration

1. Patel, Viral K., et al. "Experimental evaluation and thermodynamic system modeling of thermoelectric heat pump clothes dryer." Applied energy 217 (2018): 221-232.

TE Heating vs. Electric Resistance Heater

- Cost
  - TE modules have initial cost of ~$0.07/W.
  - Cost per unit heating capacity of a TE module increases sharply with increasing temperature differences, since capacity drops with temperature lift.
  - 4% higher cost for each 1°C higher temperature lift.



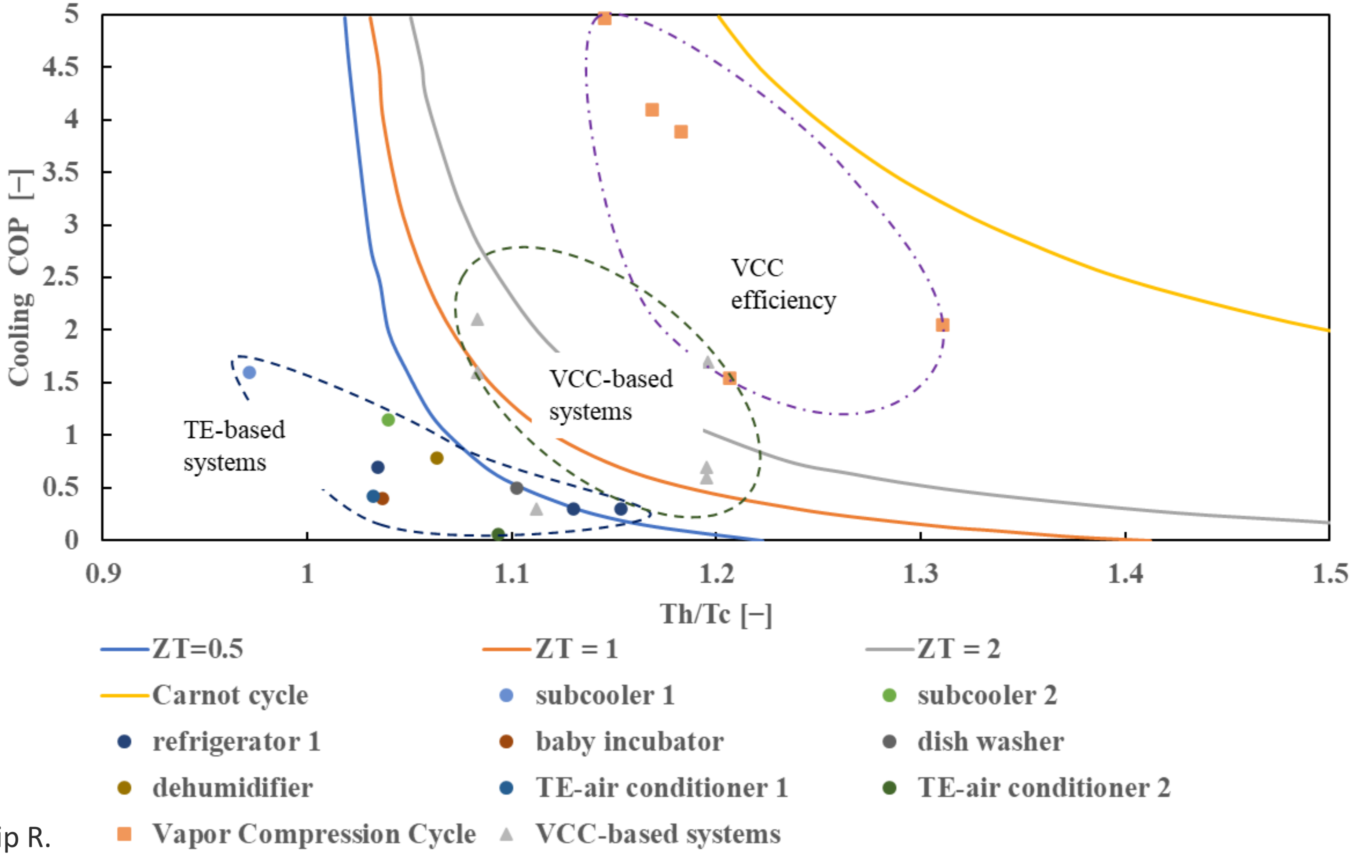
Heating capacity vs. temperature lift

- Efficiency
  - TE heating is more efficient than electric resistance heating, with $COP_{heating}$ < 1.
  - TE modules can recover energy in some cases, allowing for the reuse of otherwise wasted energy.
  - TE heating can achieve higher efficiency than electric heating in situations where both heating and cooling are used.

TE vs. Vapor Compression System (VCS)

- Efficiency

  - COPs of VCS is higher at a given temperature lift.
  - Bi_2Te_3 alloys have low $COP_{cooling}$ (<1), but are suitable for niche markets (<25 W).
  - TE elements can stabilize semiconductor lasers and cool vaccines.
  - TE systems are potential solutions for portable refrigeration, car seat coolers, and beverage coolers.
  - Appliances using Bi_2Te_3 alloys can have improved performance over electric resistance.



TE Cooling vs. VCC Cooling

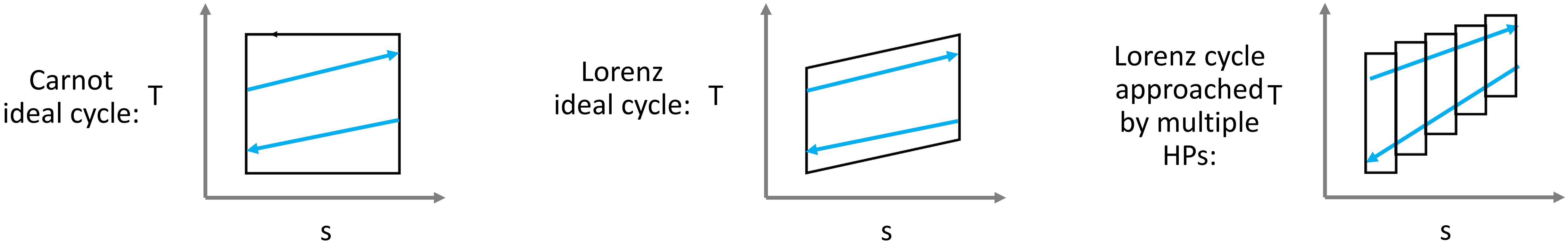
1. Adapted from “High-Potential Applications for Thermoelectric Heat Pumps in Residential Appliances,” Hanlong Wan, Kyle R. Gluesenkamp*, Wyatt Merrill, Philip R. Boudreaux, Lincoln Xue (manuscript in development)

When is TE favorable vs. VCS

- **Large glide** on one or more fluid sides can increase TE system efficiency

All else being equal, VCS systems have higher COP than TE at the same temperature lift. However, high glide applications offer opportunities for TEs to close the gap:

- VCS systems can have a significant temperature mismatch when transferring heat to or from a fluid with high glide.
- TE modules can be arranged in a series of multiple HPs, approaching the Lorenz cycle ideal instead of the Carnot.
- When at least one fluid has a large glide, some TE modules can have low lifts and high efficiency.

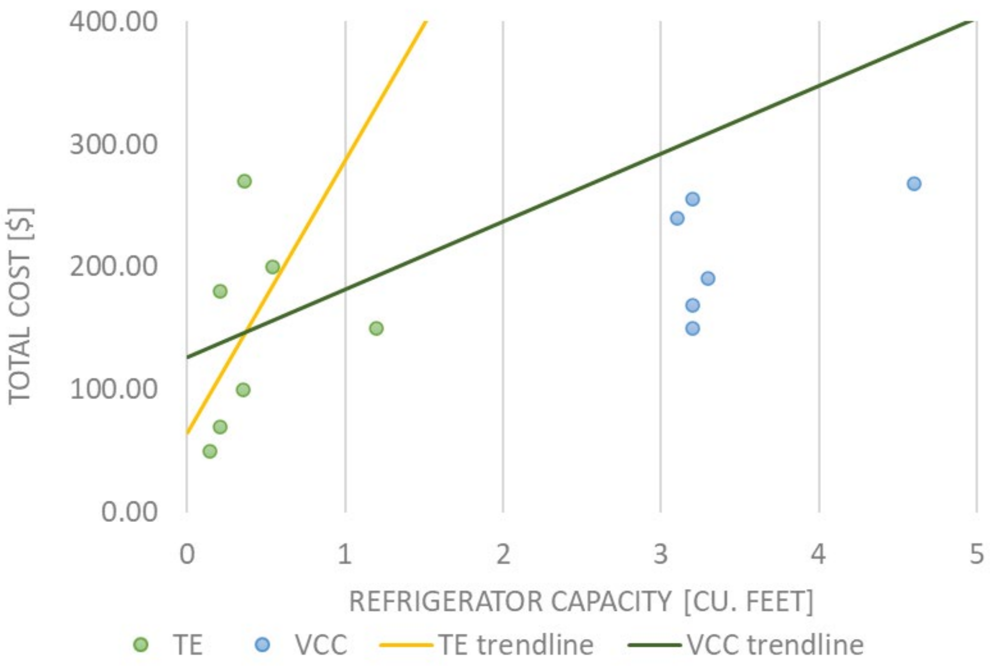


Figures: Gluesenkamp, Kyle R. "High Temperature Heat Pumps," Presented to AMO Workshop: Thermal Process Intensification: Transforming the Way Industry Uses Thermal Process Energy, December 9, 2020.

When is TE favorable vs. VCS

- TE-based systems with lower initial costs for **small HP capacities**

  - We conducted a commercial survey comparing TE-based refrigerators with VCS-based refrigerators on Amazon.
  - The cost per cubic foot of TE-based refrigerators is 4 to 5 times higher than that of VCS-based refrigerators.
  - When a small cooling capacity (e.g., 0.3 ft^3) is required, the capital cost of TE-based refrigerators is typically lower than VCS-based refrigerators.



Cost analysis for selected small refrigerators

When is TE favorable vs. VCS

- TE-based devices for **nonenergy benefits** to consumers – can facilitate new HP applications

Air Conditioner		VCC	TE
Model		KFR-26 GW	MAA1200E-115
Cooling	Capacity (W)	2,600	320
	Power (W)	880	840
	COP	2.95	0.38
	Working temperature range (°C)	18~45	<70
Heating	Capacity (W)	3,000	1,159
	Power (W)	1,000	840
	COP	3	1.38
	Working temperature range (°C)	–5~18	any
Noise level (Db)		39/49 (indoor/outdoor)	0 from TE modules and 30 from fans
Size (mm)		815 × 298 × 194 (indoor) 820 × 520 × 220 (outdoor)	470 × 302 × 216
Weight (kg)		8 (indoor) 33 (outdoor)	19.5
Life expectancy (year)		~11	~23
Equipment cost ($)		500	880

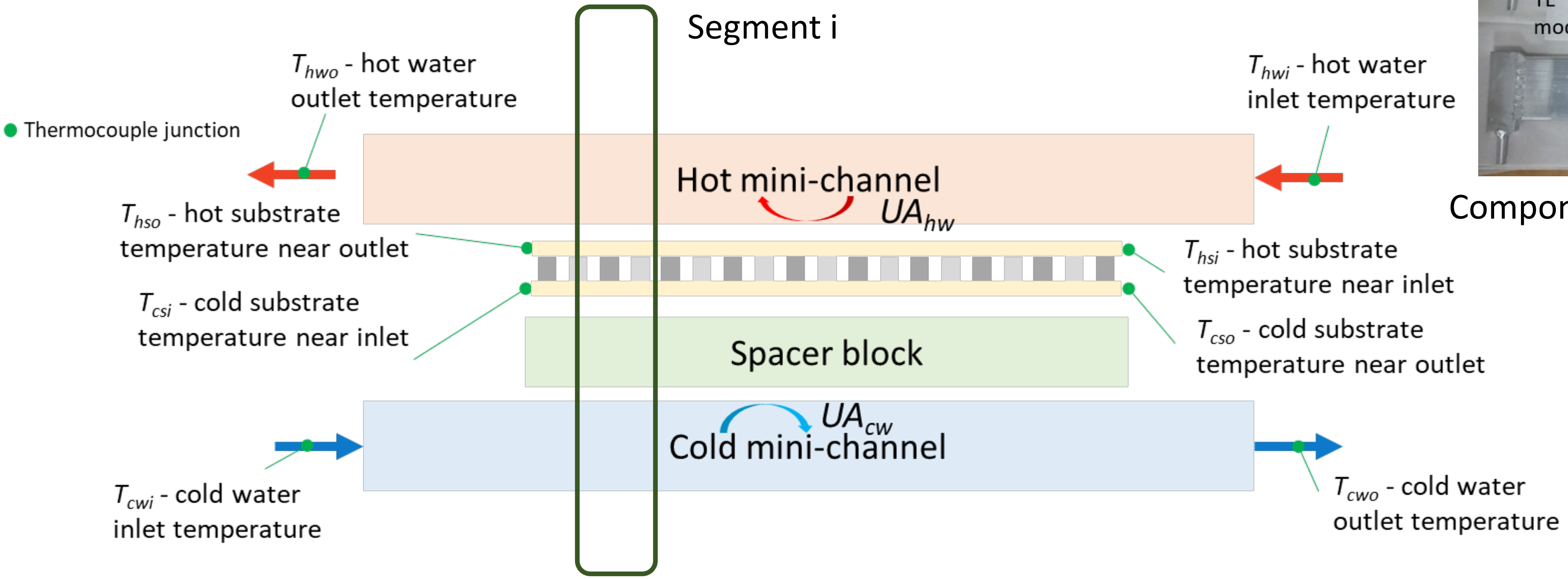
Lower noise, smaller size, lower weight, longer life

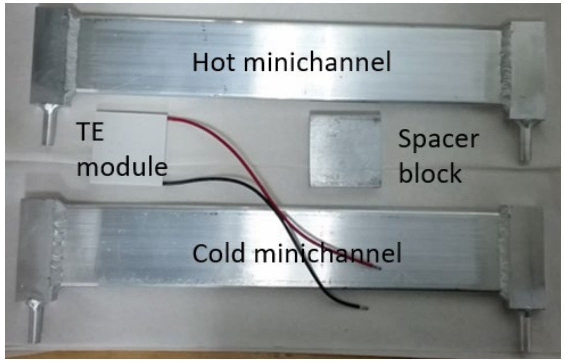
Another example: adding TEHP to dishwasher heats water more efficiently while also enhancing drying performance

1. Riffat SB, Qiu G. Comparative investigation of thermoelectric air-conditioners versus vapour compression and absorption air-conditioners. Applied Thermal Engineering 2004;24:1979–93.

Thermoelectric Heat Pump Modeling

- A segment-by-segment TEHP model was developed.



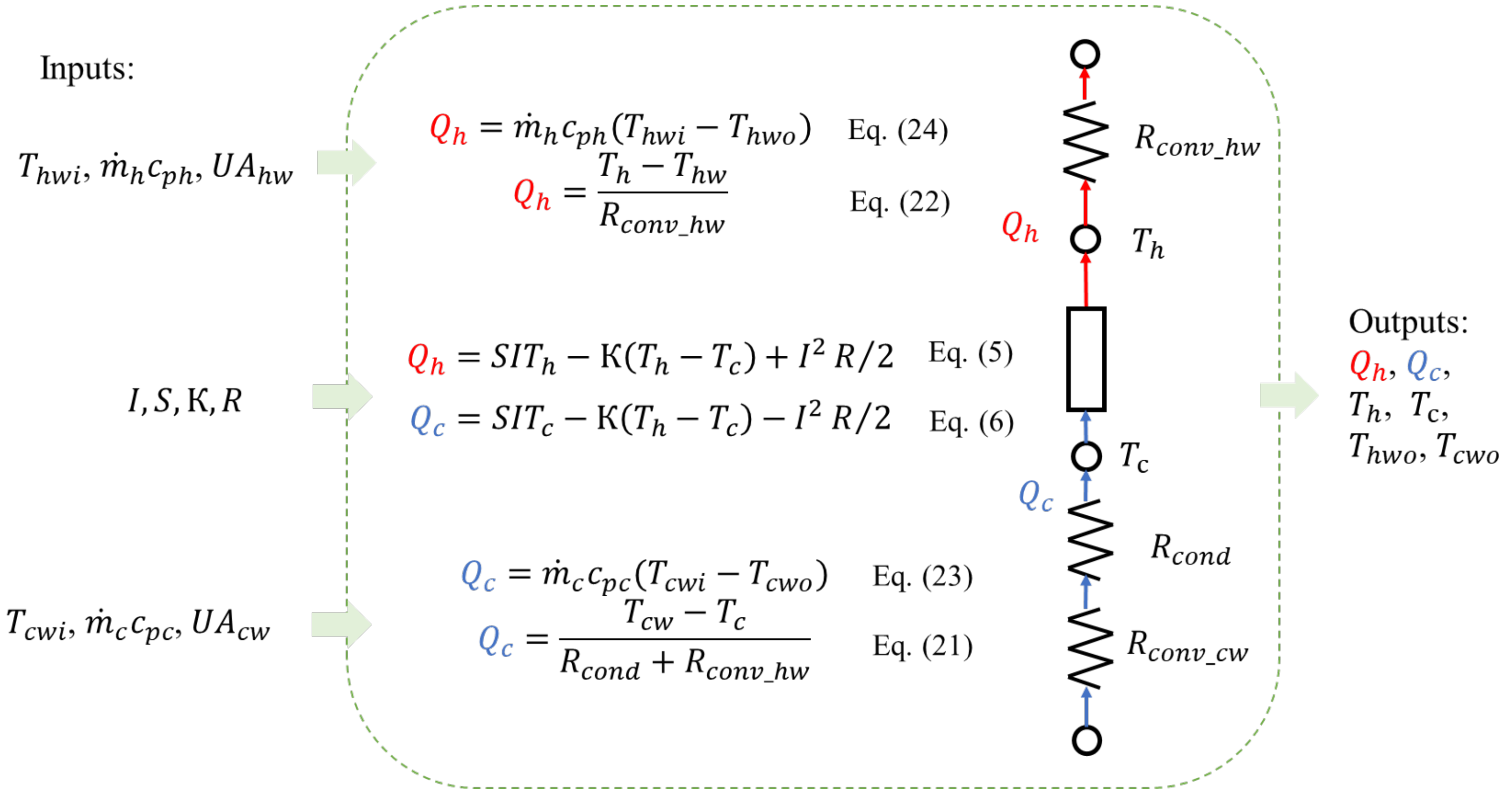


Components before assembling

1. Wan, Hanlong, et al. "A Thermodynamic Model of Integrated Liquid-to-Liquid Thermoelectric Heat Pump Systems." International Journal of Refrigeration (2023).

Modeling Approaches

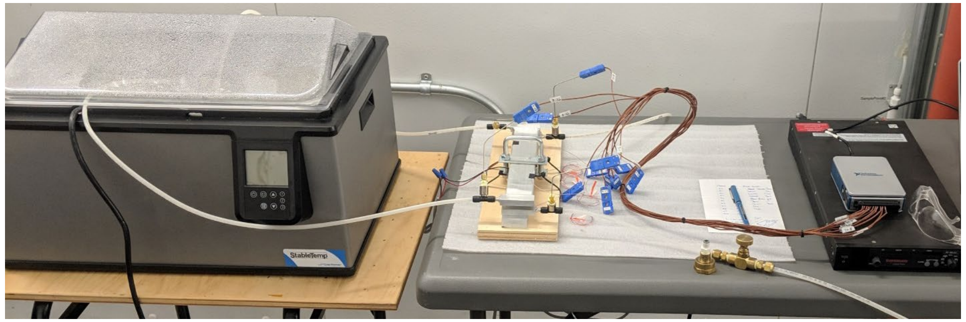
- Resistance Network



Correlations Applied

Parameters	Phase Change	Conditions	Correlation Name	Equations
Pressure Drop	Single Phase	–	Fractional pressure drop (Bai and Bai, 2014)	$\Delta P = f \cdot (l/d) \cdot (G^2/\rho_l)$
	Two Phase	–	Friedel, (1979)	–
HTC	Single Phase	–	Dittus and Boelter, (1985)	$Nu_D = 0.023 Re_D^{4/5} \mathrm{Pr}^{1/3}$
	Two Phase	Evaporating (hot side)	Zhang et al., (2019)	–
		Condensing (cold side)	Shah, (2019)	–

Quasi-steady-state Performance

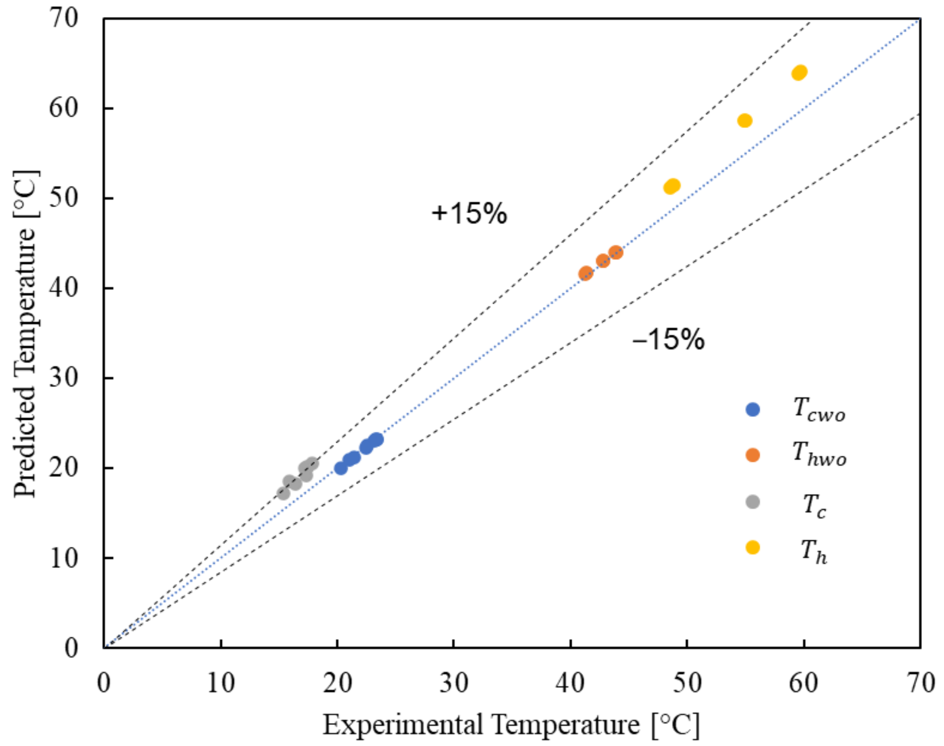


Laboratory Test

Segment	1	2	3	4	5	6	7	8	9	10
T_{hw} [°C]	41.37	41.17	40.96	40.76	40.55	40.35	40.15	39.94	39.74	39.53
T_h [°C]	51.80	51.60	51.38	51.18	50.99	50.74	50.55	50.35	50.15	49.96
T_c [°C]	18.83	18.78	18.76	18.70	18.65	18.60	18.55	18.49	18.44	18.39
T_{cw} [°C]	21.39	21.35	21.30	21.26	21.21	21.17	21.12	21.08	21.03	20.99

Simulation results (I = 5 A, 10 segments).

Comparison between experimental and model-predicted temperature



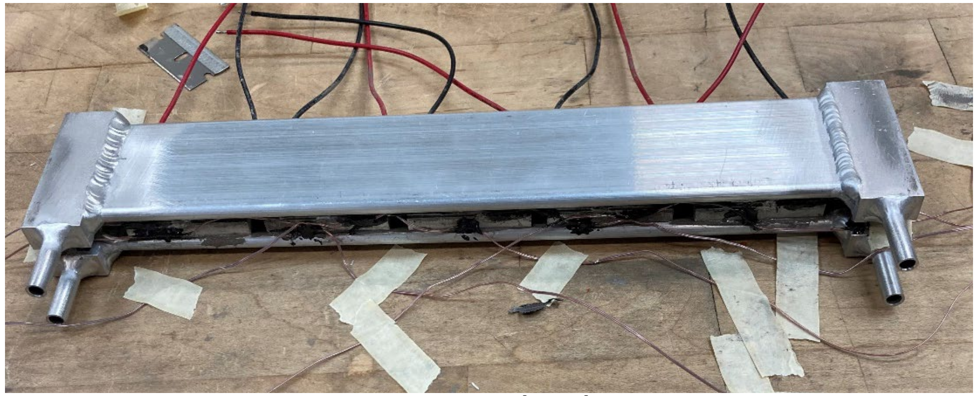
TEHP steady-state performance

Method	S (V·K^{-1})	R (Ω)	K (W·m^{-1}·K^{-1})	RME_DT (%)	RME_DT$_w$ (%)	RME_Q$_c$ (%)	RME_Q$_h$ (%)	COP$_c$(-)
1	0.045	1.69	0.398	1.93	0.75	5.96	6.03	0.4
2	0.054	1.52	0.730	2.04	1.43	23.25	6.91	0.5
3	N/A	N/A	N/A	2.80	1.94	24.44	9.20	0.5

1. Patel, Viral, Kyle R. Gluesenkamp, and Philip R. Boudreaux. Thermoelectric heat pump performance characterization. Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States), 2021.

Transient Performance

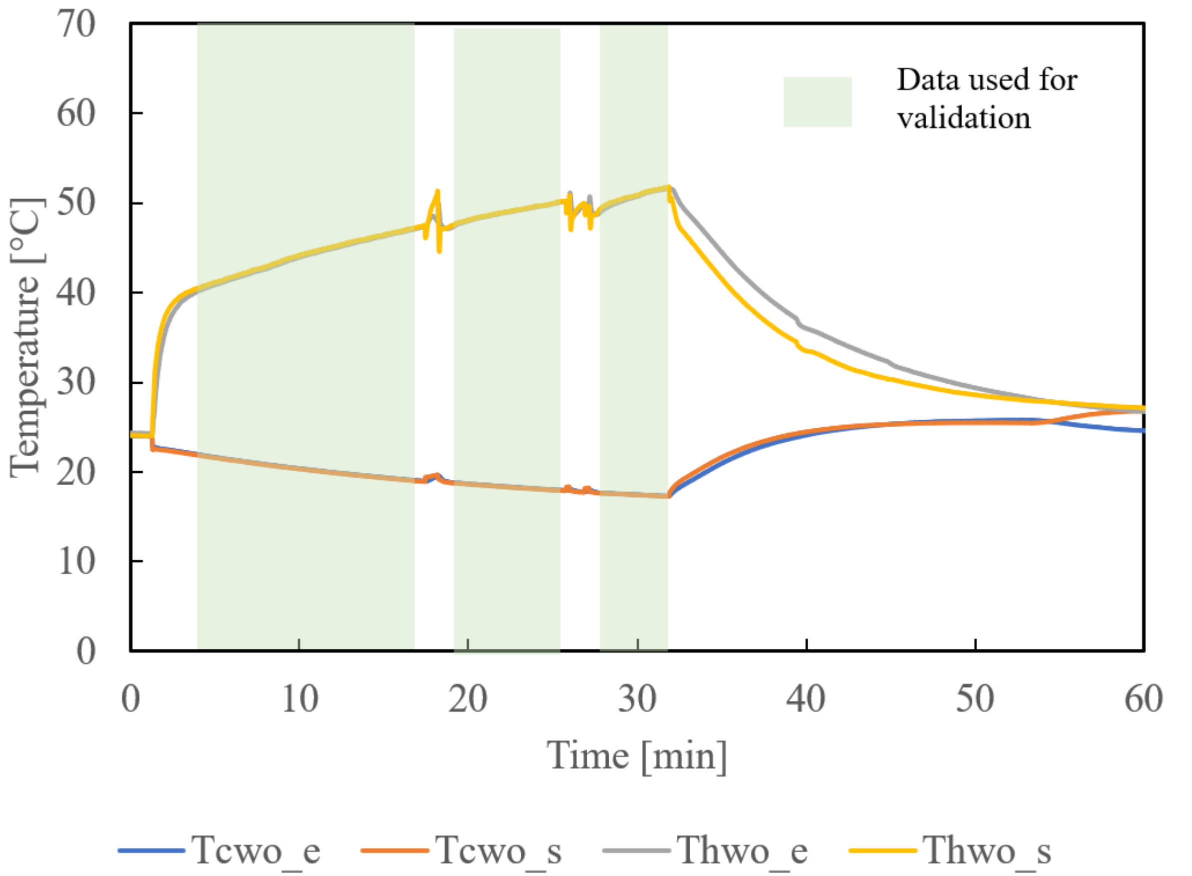
- Dishwasher tests data was used to validate the transient performance.



TEHP Outlook

TEHP transient performance

Method	S (V/K)	R (Ω)	K (W/(m·K))	RME_DT (%)	RME_DT$_w$ (%)	RME_Q$_c$ (%)	RME_Q$_h$ (%)	COP$_c$(-)
1	0.045	1.69	0.398	34.97	0.52	6.78	8.53	0.6
2	0.054	1.52	0.73	33.05	0.56	11.60	7.05	0.6
3	N/A	N/A	N/A	35.10	0.61	7.09	8.84	0.6



Experimental and model-predicted outlet water temperature

Conclusions

Overall

- Appliances with TE modules composed of Bi_2Te_3 alloys have COPs below 1 but are suitable for niche markets and specialized applications;
- TE heating has a close cost and higher efficiency than electric heaters;
- TEHP systems are less energy efficient than VCC-based systems but have advantages in certain situations, such as large glides on one fluid side or non-energy benefits outweighing disadvantages.

TEHP model

- Water-to-water TEHP model can achieve 10% RME for heating and 10%-25% for cooling at 30 K temperature lift;
- TE module properties can be constant for temperature lifts below 30 K, with TE surface temperature having a major impact on capacity and efficiency;
- Peltier effect and heat conduction complement each other for heating and cooling capacity, with S and K determined by measuring the voltage from the Seebeck effect at zero current;
- System COP can be calculated from the TE sides to reduce uncertainty by up to 95% for regular TEHP applications with small inlet and outlet water temperature differences.

Possible Future Works

- Investigation of advanced materials is crucial for improving TE technologies, such as Bi_2Te_3 alloys and alternative materials and structures.
- Heat sink and heat exchanger design need to be optimized to improve the cooling or heating performance of TEHPs.
- Device structural design and system optimization are required for the stable cooling or heating performance of TE modules.
- The market for TE systems is steadily growing and expected to reach $741 million in 2025, with potential applications in various fields such as medical, automotive, industrial, and residential appliances.

- **Thank you!**
  - **Question?**

Acknowledgment

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