Exploration of Heat-Driven Ejector High-Temperature Heat Pumps (HTHPs)

Pengtao Wang, Stephen Kowalski, Cheng-Min Yang, Jian Sun

Zhiming Gao, and Kashif Nawaz*

Oak Ridge National Laboratory

*Corresponding author. Tel.: +1-865-241-0972. *E-mail address:* nawazk@ornl.gov

Outlines

- Introduction
- HDHP with a Binary Fluid Ejector
- Working fluids for a Binary Fluid Ejector
- Performance of Ejector-based HDHPs
  a. Binary Fluid Ejectors
  b. Single Fluid Ejectors
- Conclusions
- Acknowledgement

➢ *Current R&D on HTHPs*

- High temperature heat pumps (T_{sink}> 100 ℃) for industrial decarbonization
- Majority operates with refrigerant vapor compression cycles using electric-driven mechanical compressor

➢ *Challenges of high T_{sink} on mechanical compressors in VCHPs*

- overheating
- compatibility and stability of the lubricant oil
- risk of wet compression for low GWP refrigerants
- limited drop-in replacement of refrigerants

➢ *Opportunities for heat-driven HTHPs (HDHPs) using an ejector*

- Supersonic ejector is used as a thermocompressor
- No moving parts for high reliability
- Simple structure for low cost
- Scalable to large systems and multi-stage systems

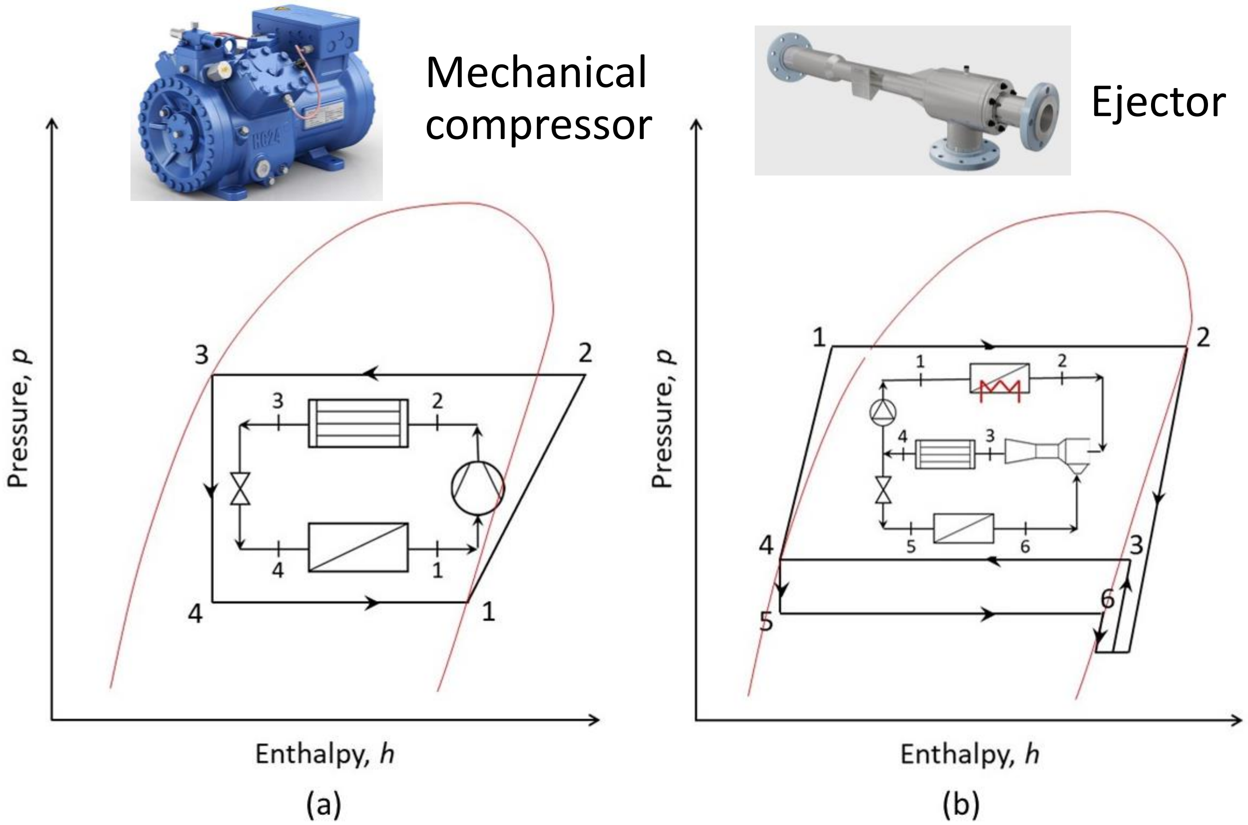


Fig. 1 Schematic of thermodynamic cycles of HTHPs.
(a) mechanical compressor, and (b) ejector thermocompressor.

Introduction

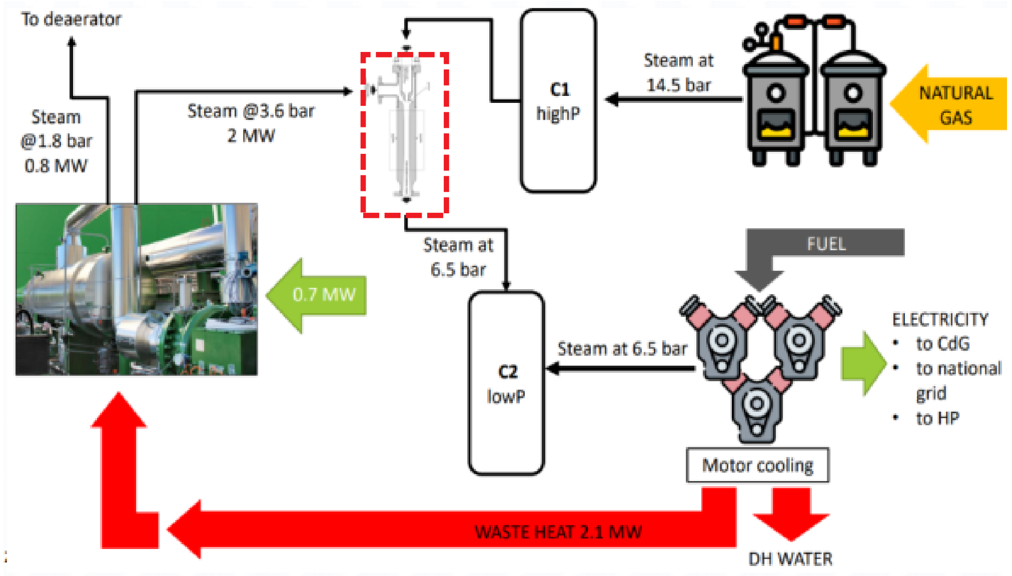
➢ *State-of-the-art ejector technologies*

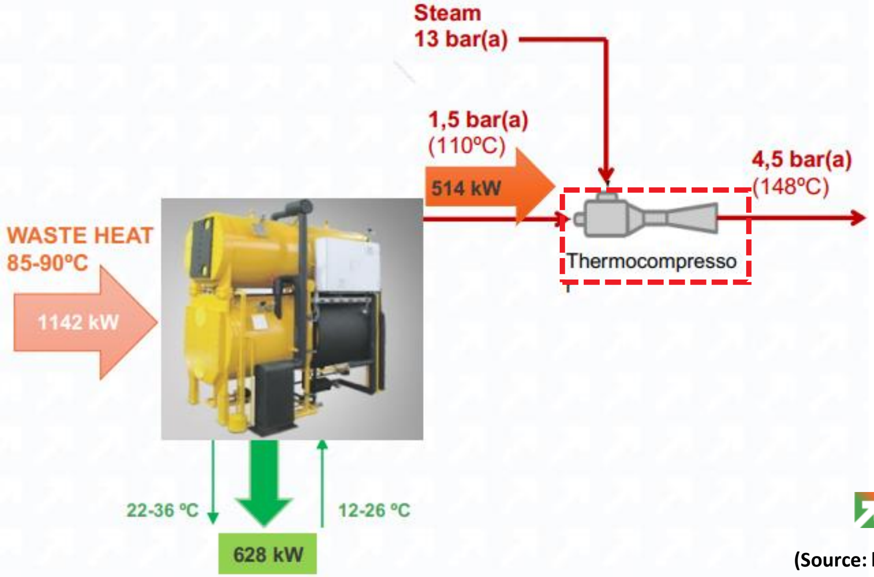
Ejector refrigeration systems: extensive R&D efforts; attractive with available waste heat or utilizing solar thermal energy;

Ejector-based HDHPs: open-loop HTHP, limited R&D efforts;

Europe PUSH2HEAT demo sites: 1) Paper industry in Italy, CHP plant

2) Chemical plant in Spain, absorption heat transformer





(Source: https://push2heat.eu/demo-sites/)

Ejector-based HDHP in Europe PUSH2HEAT project. (a) Paper industry, (b) Chemical industry.

Introduction

➢ *Working fluids in a supersonic ejector*

Primary fluid (PF): the motive steam with high temperature/pressure (T&P);
Secondary fluid (SF): the refrigerant vapor with low T&P;
Mixed fluid (MF): saturated vapor with middle T&P.

➢ *Potential technical barriers to ejector-based HDHPs*

- Low coefficient of performance (COP)
- Small lift temperature or compression ratio
- Significant performance degradation in "off-design" conditions

➢ *Motivation for this study*

- Binary fluids for a higher COP of ejector-based HDHPs

$$COP_{\mathrm{HDHP}} = 1 + \omega \frac{h_{lv,SF}}{\Delta h_{sh,PF}+h_{lv,PF}} \approx 1 + \omega \frac{\Delta h_{SF}}{\Delta h_{PF}}, \text{ where } \omega = \frac{\dot{m}_{SF}}{\dot{m}_{PF}}$$

A higher ω and/or a larger $\frac{h_{lv,SF}}{h_{lv,PF}}$ yield a higher COP.

- Technical feasibility of ejector-based HDHPs with $T_{\mathrm{sink}} > 100$ ℃

HDHP with a Binary Fluid Ejector

➢ *Thermodynamic model of an HDHP using a binary fluid ejector*

Gravity-based or thermal-based separator for effectively separating the PF and SF.

The thermodynamic model of ejector-based HDHP is built with the conservation of mass and energy.

A gas-dynamic model of ejector predicts the performance of the ejector.

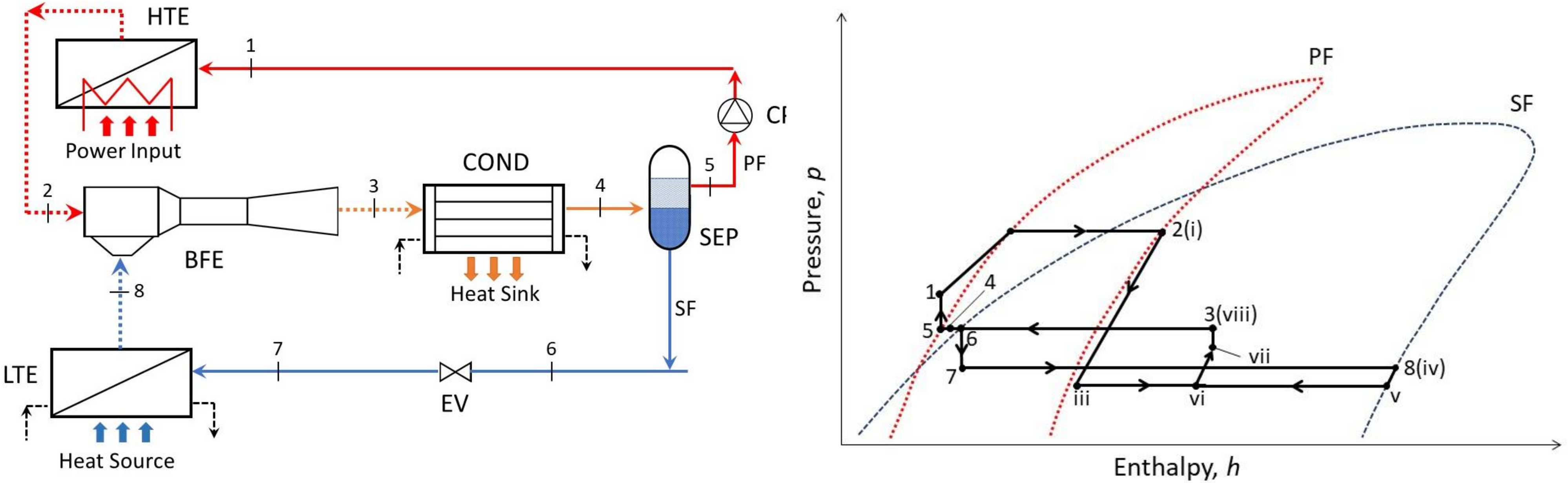


Fig. 2 Schematic of a heat-driven ejector HTHP. (a) System configuration, (c) p-h diagram.

HDHP with a Binary Fluid Ejector

- *Gas-dynamic model of the binary fluid ejector*
  - Gas dynamic process in an ejector

i->ii, high T/P steam of PF accelerates into a supersonic flow, creating a vacuum at the nozzle exit plane (NXP).

iv->v, low T/P vapor of SF accelerates into a sonic flow at the hypothetical throat;

ii->iii, PF expands in the converging section of the mixing chamber;

iii+v->vi, PF and SF mix under a constant p_M;

vi->vii, a normal shock wave occurs, creating a compression effect;

vii->viii, mixed PF-SF diffuses in the diffuser.

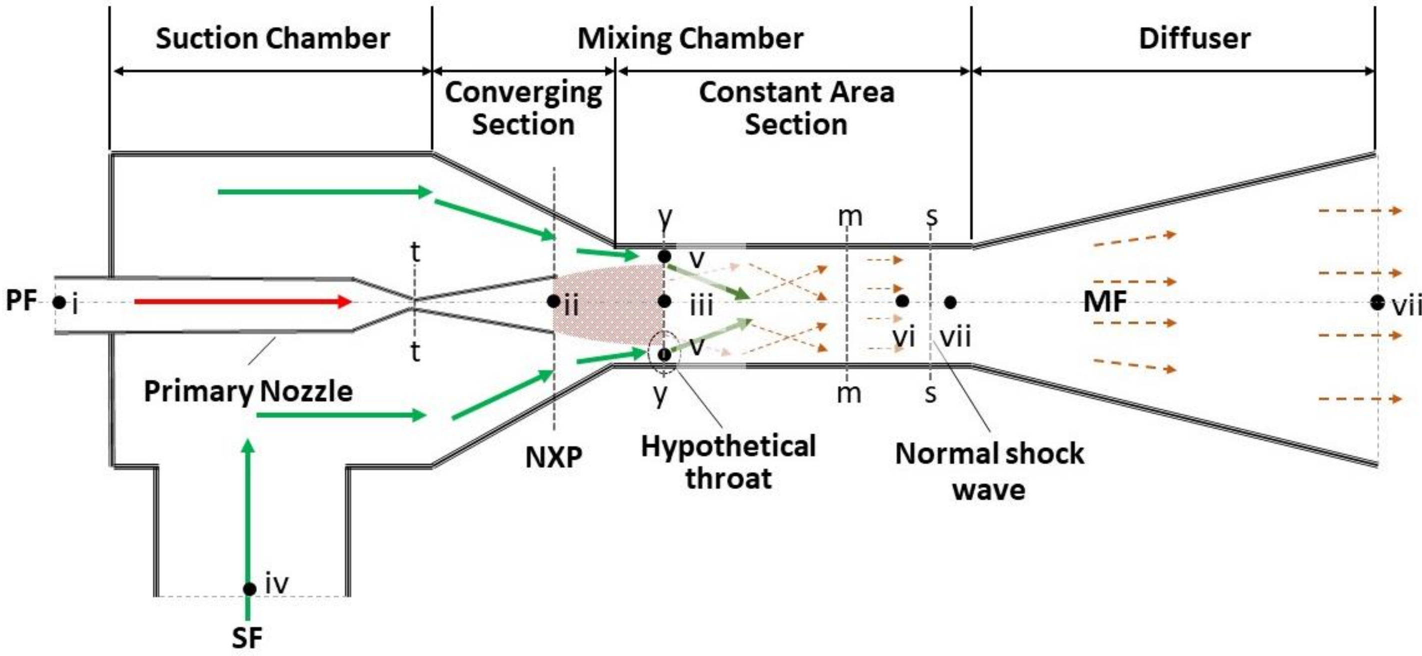


Fig. 2 Schematic of a heat-driven ejector HTHP. (b) gas-dynamic process within an ejector.*

*Wang, Pengtao and AbuHeiba, Ahmad and Spitzenberger, Jeremy and Kowalski, Stephen and Ma, Hongbin and Nawaz, Kashif, Thermodynamic Analysis of a Two-Stage Binary-Fluid Ejector Heat Pump Water Heater. Available at SSRN: https://ssrn.com/abstract=4155125 or http://dx.doi.org/10.2139/ssrn.4155125

HDHP with a Binary Fluid Ejector

- Governing equations

  Energy conservation of PF through the primary nozzle,

$$h_{\rm iii} = (1-\eta_{\rm N})h_{\rm i} + \eta_{\rm N} h_{\rm iii,is}\ ,\ h_{\rm v,is} = h(s_{\rm i}, p_{iii}),\ \text{and}\ h_{\rm v,is} = h(s_{\rm iv}, p_{\rm v}).$$

  For the choked SF flow, $h_{\rm v,is} = h(s_{\rm iv}, p_{\rm v})$ with $\eta_{\rm S}$, and $V_{\rm v} = C_{\rm v}$.

  In the mixing process, $p_{\rm iii} = p_{\rm v} = p_{\rm vi} = p_{\rm M}$, $\phi_{\rm M}=\sqrt{\eta_{\rm M}}$

$$\phi_{\rm M}(\dot m_{\rm PF} V_{\rm iii} + \dot m_{\rm SF} V_{\rm v}) = (\dot m_{\rm PF} + \dot m_{\rm SF}) V_{\rm vi},$$

$$(\dot m_{\rm PF} + \dot m_{\rm SF})\left(h_{\rm vi} + \frac{1}{2}V_{\rm vi}^2\right) = \dot m_{\rm PF}\left(h_{\rm iii} + \frac{1}{2}V_{\rm iii}^2\right) + \dot m_{\rm SF}\left(h_{\rm v} + \frac{1}{2}V_{\rm v}^2\right).$$

  Acrossing the shock wave,

$$\rho_{\rm vii} V_{\rm vii} = \rho_{\rm vi} V_{\rm vi},\ p_{vii} + \rho_{vii} V_{vii}^2 = p_{vi} + \rho_{vi} V_{vi}^2,\ \text{and}\ h_{vii} + \frac{1}{2}V_{vii}^2 = h_{vi} + \frac{1}{2}V_{vi}^2.$$

  In the diffuser, $h_{\rm viii,is} = h_{\rm vii} + \eta_{\rm D}\frac{1}{2}V_{\rm vii}^2$.

  The discharged mixed fluid, $p_{\rm viii} = p(h_{\rm viii,is}, s_{\rm viii})$ and $s_{\rm viii} = s_{\rm vii}$.

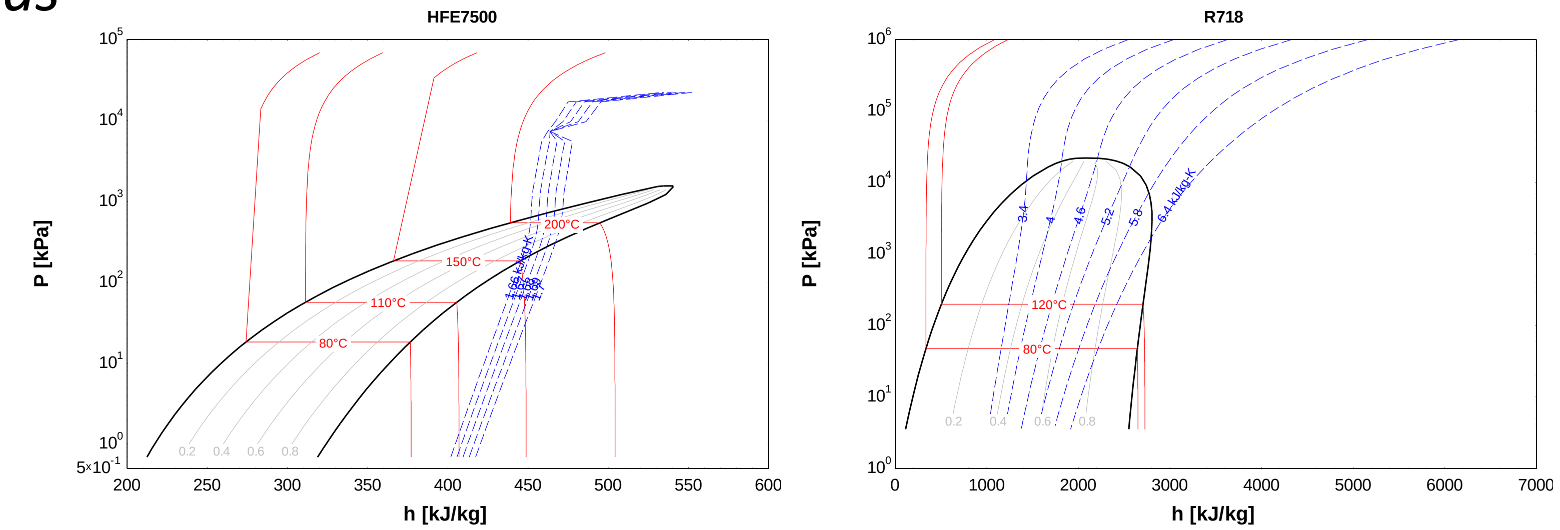
- Inputs: Inlet parameter of PF and SF, $\dot m_{\rm PF}$, $T_{\rm i}$, $p_{\rm i}$, $T_{\rm iv}$, and $p_{\rm iv}$; ejector component efficiency, $\eta_{\rm N}$, $\eta_{\rm S}$, $\eta_{\rm M}$, and $\eta_{\rm D}$.
- Outputs: ω_{max} ($\dot m_{\rm PF,max}$), $T_{\rm viii}$ and $p_{\rm viii}$.

Working fluids for a Binary Fluid Ejector

- *Selection criteria for working fluids*
  - $MW_{PF} > MW_{SF}$ for a high ω;
  - $h_{lv,PF} << h_{lv,SF}$ for a high COP;
  - Large difference in density for gravity-driven separation, or large difference in normal boiling point for thermal-driven Separation.
- *Selected working fluids*

  PF: HFE7500

  SF: R718 (water)



P-h diagrams of working fluids for binary fluid ejector.

Table 2. Working Fluids for the ejector-HDHPs.

Fluids	Formula	MW	NBP [℃]	T_{cr} [℃]	P_{cr} [MPa]	h_{lv}* [kJ/kg]	ρ [kg/m³]	GWP	Group
HFE7500	$C_9H_5F_{15}O$	414	128.4	261.0	1.55	84.0@140℃	1,560	90	HFE
R718	H_2O	18	99.97	373.9	22.064	2,333@70℃	1,000	0	Natural

Performance of Ejector-based HDHPs

➢ *Operating parameters of ejector-driven HDHPs*

T_{sink} = 100–130°C, ΔT_{lift} = 10–30°C, $T_{sink} = T_{sink} - \Delta T_{lift}$,
T_{HTE} = 190–260°C; $P_{HTE,max}$ = 1.5 MPa for HFE7500, and $P_{HTE,max}$ = 4.7 MPa for R718.
η_N = 0.92, η_S = 0.86, η_M = 0.95, and η_D = 0.81.

➢ *Performance of HDHPs with binary fluid ejectors (BFEs)*

- Effects of T_{HTE}
  - An optimal generating temperature of PF in the HTE, $T_{HTE,opt}$ = 240℃, for the entrainment ratio, ω_{BFE}.
  - ω_{BFE} dominates the COP of ejector-driven HDHPs.
  - A lower ΔT_{lift} for a higher ω_{BFE} and COP_{HP}.

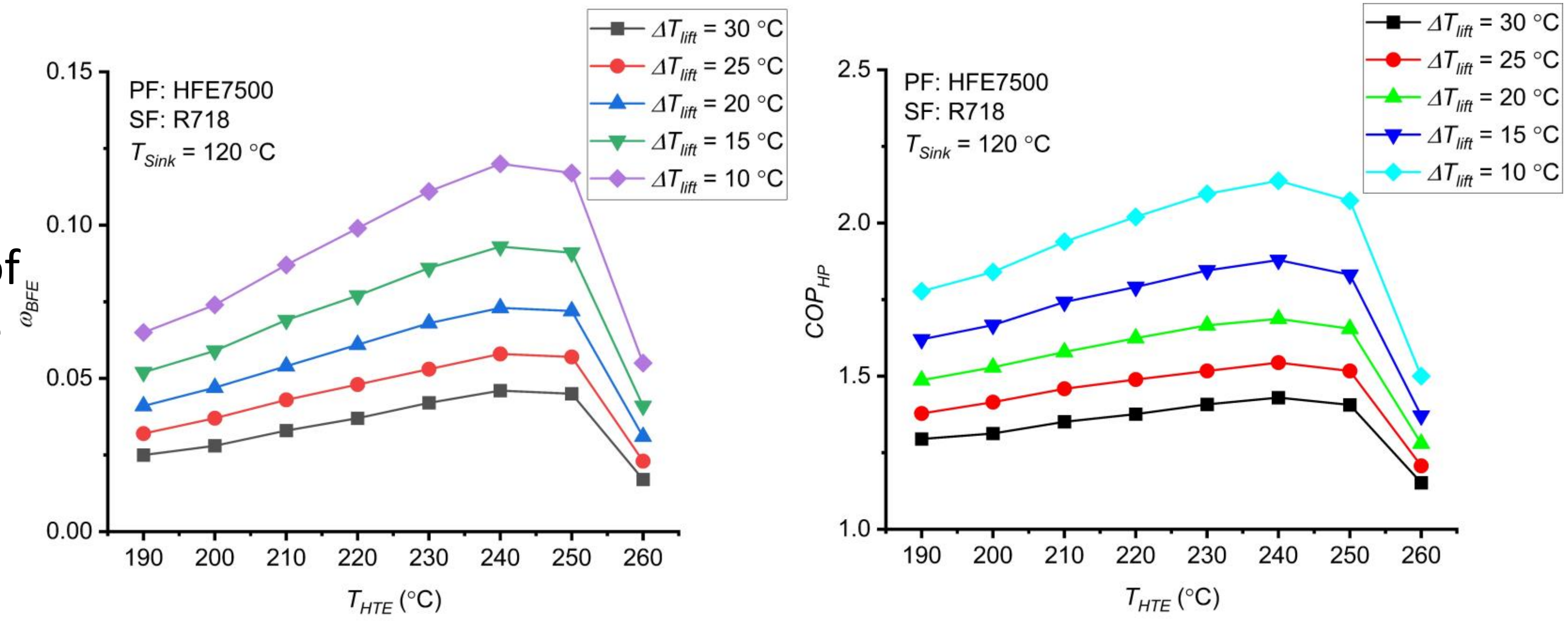


Fig. 3 Typical performance of BFEs and BFE-HDHPs. (a) Entrainment ratio and (b) COP.

Performance of Ejector-based HDHPs

14th IEA HEAT PUMP CONFERENCE

- *Performance of HDHPs with binary fluid ejectors (BFEs)*
- The optimum performance of BFEs and BFE-HDHPs

- $T_{HTE,opt}$ = 240°C for $\omega_{BFE,max}$ and $COP_{HP,max}$.
- *ΔT_{lift} and T_{sink}* significantly affect $\omega_{BFE,max}$ and $COP_{HP,max}$.
- A lower T_{sink} and ΔT_{lift} for a higher $\omega_{BFE,max}$ and $COP_{HP,max}$.

At ΔT_{lift} = 10 °C, T_{sink}=110°C, $\omega_{BFE,max}$ = 0.16, and $COP_{HP,max}$ = 2.48;

At ΔT_{lift} = 30 °C, T_{sink}=130°C, $\omega_{BFE,max}$ = 0.04, and $COP_{HP,max}$ = 1.39.

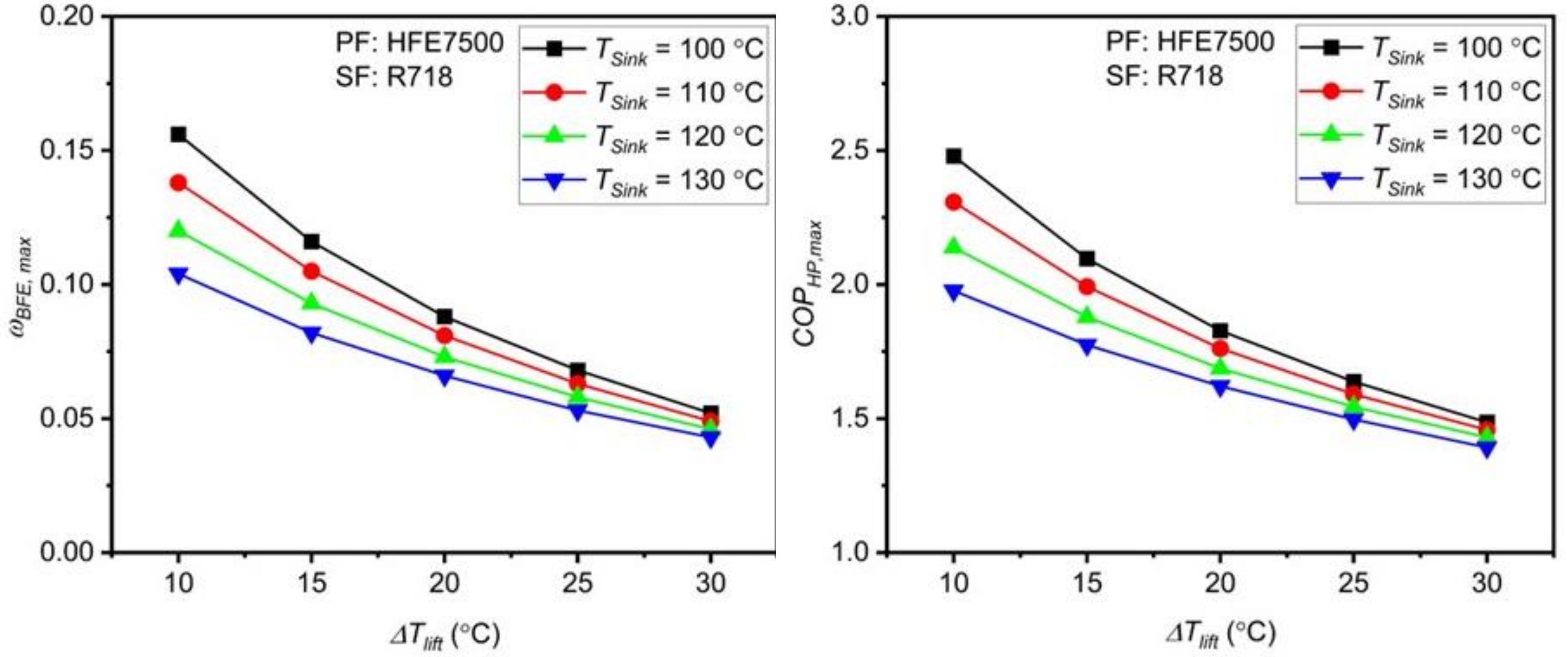


Fig. 4 The maximum performance of BFEs and BFE-HDHPs. (a) Maximum entrainment ratio and (b) maximum COP

Performance of Ejector-based HDHPs

➢ *Performance of HDHPs with single fluid ejectors (SFEs)*

- SFEs using HFE7500

▪ $T_{HTE,opt}$ = 230°C for $\omega_{BFE,max}$ and $COP_{HP,max}$.

▪ *A much higher* $\omega_{BFE,max}$ but slightly lower $COP_{HP,max}$, compared with BFEs.

▪ $\omega_{BFE,max}$ and $COP_{HP,max}$ are less sensitive to T_{sink}, compared with BEFs.

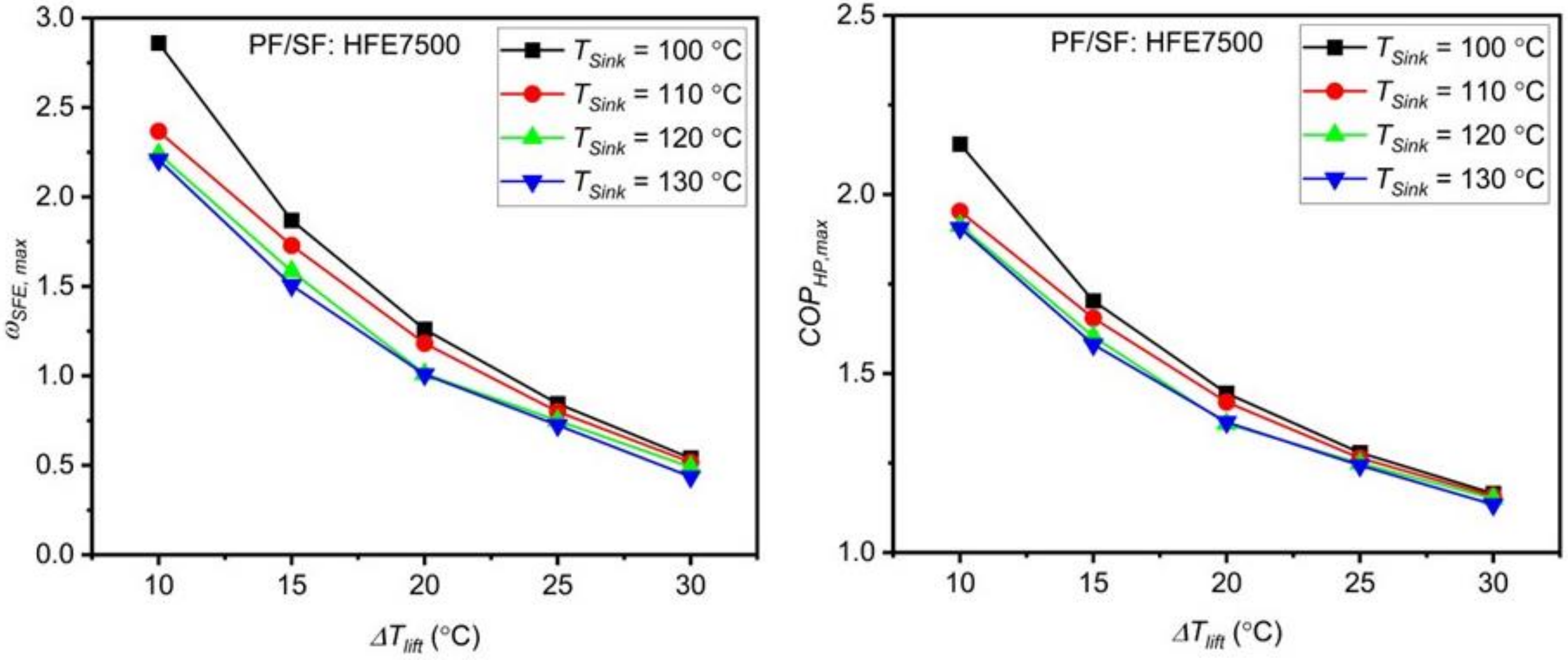


Fig. 5. The maximum performance of SFEs and SFE-HDHPs with HFE7500. (a) Maximum entrainment ratio and (b) maximum COP.

Performance of Ejector-based HDHPs

➢ *Performance of HDHPs with single fluid ejectors (SFEs)*

- SFEs using R718
  - Similar trends to SFEs using HFE7500.
  - $T_{HTE,opt}$ = 260°C for $\omega_{BFE,max}$ and $COP_{HP,max}$.
  - $\omega_{BFE,max}$ and $COP_{HP,max}$ are independent on T_{sink}.

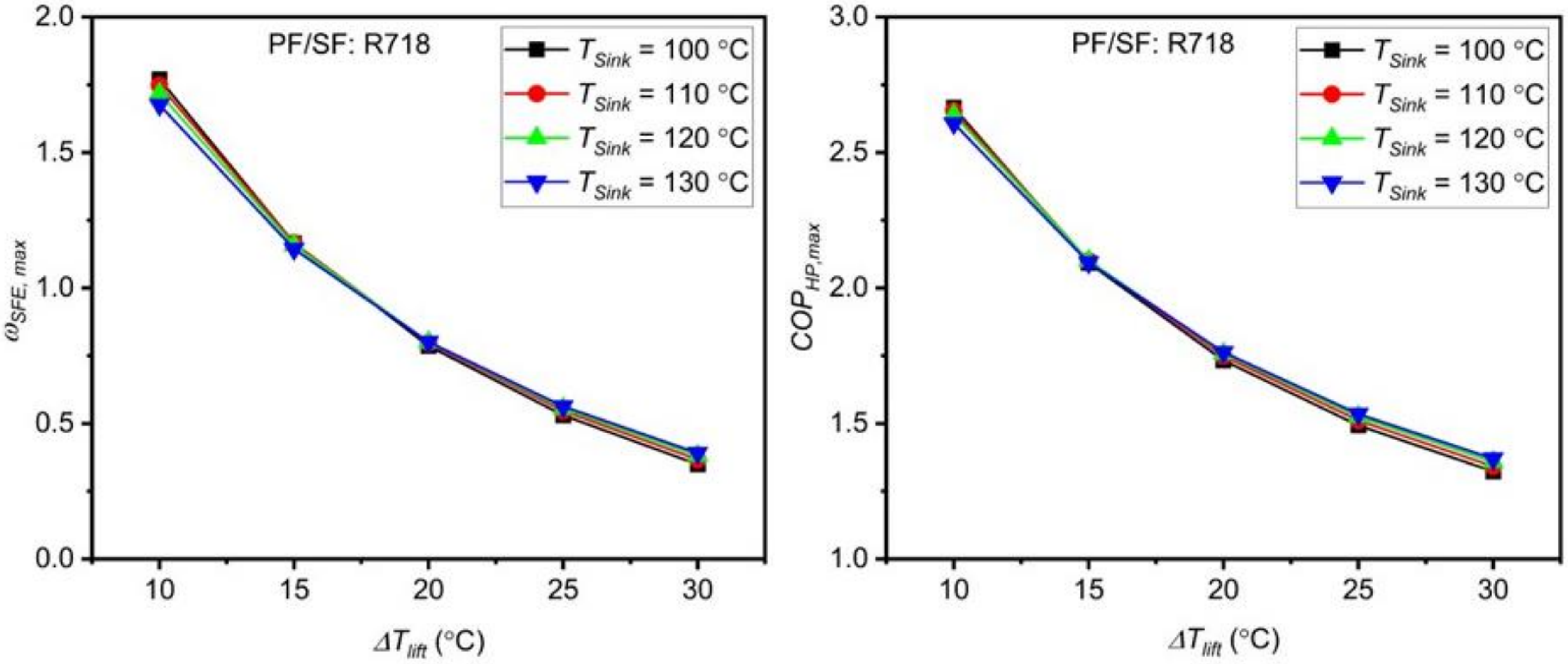
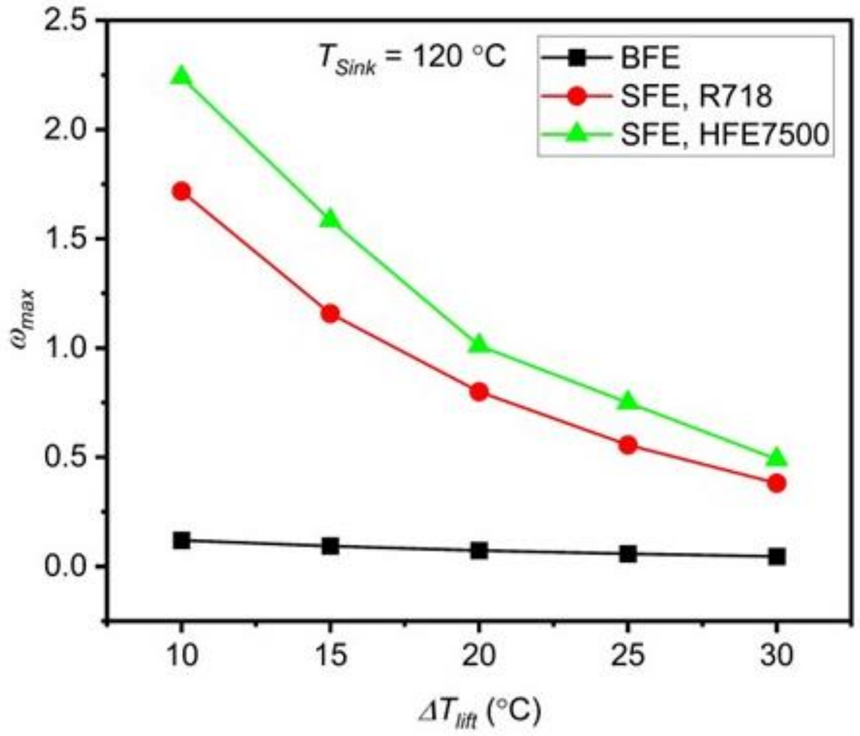


Fig. 6. The maximum performance of SFEs and SFE-HDHPs with R718. (a) Maximum entrainment ratio and (b) maximum COP.

Performance of Ejector-based HDHPs

➢ *Comparison of BFEs and SFEs*

- BFEs only give slightly better performance at a high ΔT_{lift} (> 25℃), due to extremely low $\omega_{BFE,max}$ (< 0.1) in BFEs.
- SFEs operating with R718 give the best performance at a low ΔT_{lift} (< 25℃).
- Ejector-driven HDHPs has η_{Carnot} of 6.7%-10.4% for T_{sink} = 120°C and ΔT_{lift} = 10–30°C. This is much lower than the state-of-the-art HTHPs with η_{Carnot} of 40%-60%.



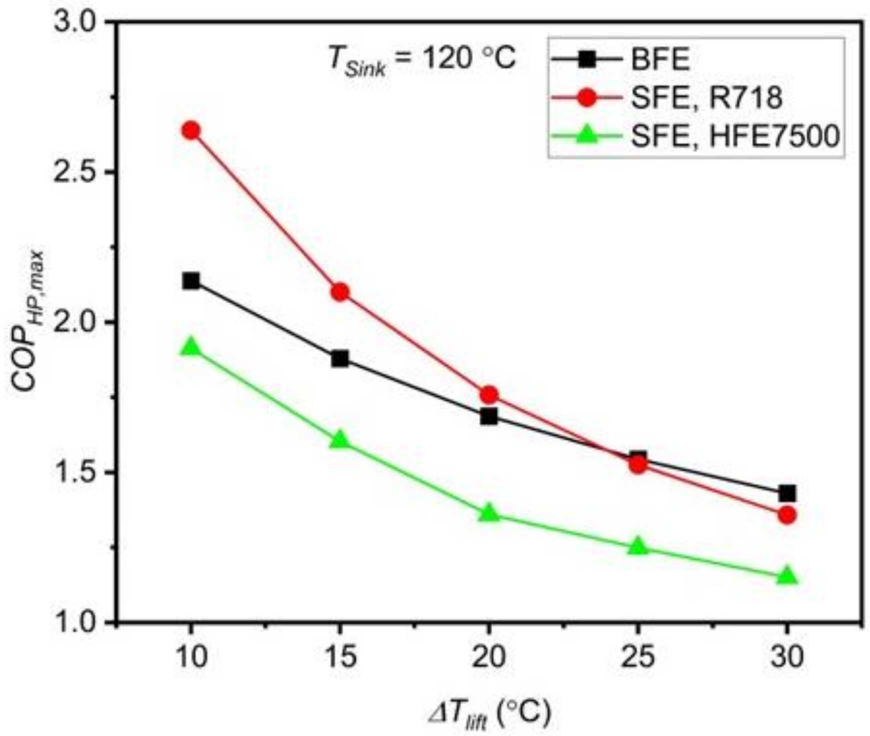


Fig. 7. Comparation of BFE-HDHPs and SFE-HDHPs.
(a) Maximum entrainment ratio and (b) maximum COP.

Conclusions

- The COP of close-loop, ejector-based HDHPs is much lower than that of state-of-art VCHPs.
- The binary-fluid ejectors (BFEs) are promising to improve the COP of ejector-based HDHPs. However, selecting the binary fluid pairs is critical. The benefits of BFE were not realized using HFE7500/R718 due to the extremely low entrainment ratio.
- Single-Fluid Ejector (SFE) using R718 could be one of the candidates for ejector-driven HDHPs. There is a potential for improved performance if an open loop could be implemented.
- Unique industrial applications of open-loop, ejector-based HDHP systems are required to compensate for their low COP.

Acknowledgement

This work was sponsored by the U. S. Department of Energy's Building Technologies Office under Contract No. DE-AC05-00OR22725 with UT-Battelle, LLC. This research used resources at the Building Technologies Research and Integration Center, a DOE Office of Science User Facility operated by the Oak Ridge National Laboratory. The authors would like to acknowledge Mr. Antonio Bouza, Technology Manager, U.S. Department of Energy Building Technologies Office (BTO).

ORNL's Building Technologies Research and Integration Center (BTRIC) is a DOE-designated national user facility. BTRIC is comprised of 60,000+ ft^2 of lab facilities conducting RD&D to support the DOE mission to equitably transition America to a carbon pollution-free electricity sector by 2035 and carbon free economy by 2050.