Performance Analysis of High Temperature Heat Pumps with Two-Phase Ejectors

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Outlines

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- Theoretical Model of Two-Phase Ejector
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- Results and Discussion
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Background

➢ *HTHP with T_{sink} >100℃*

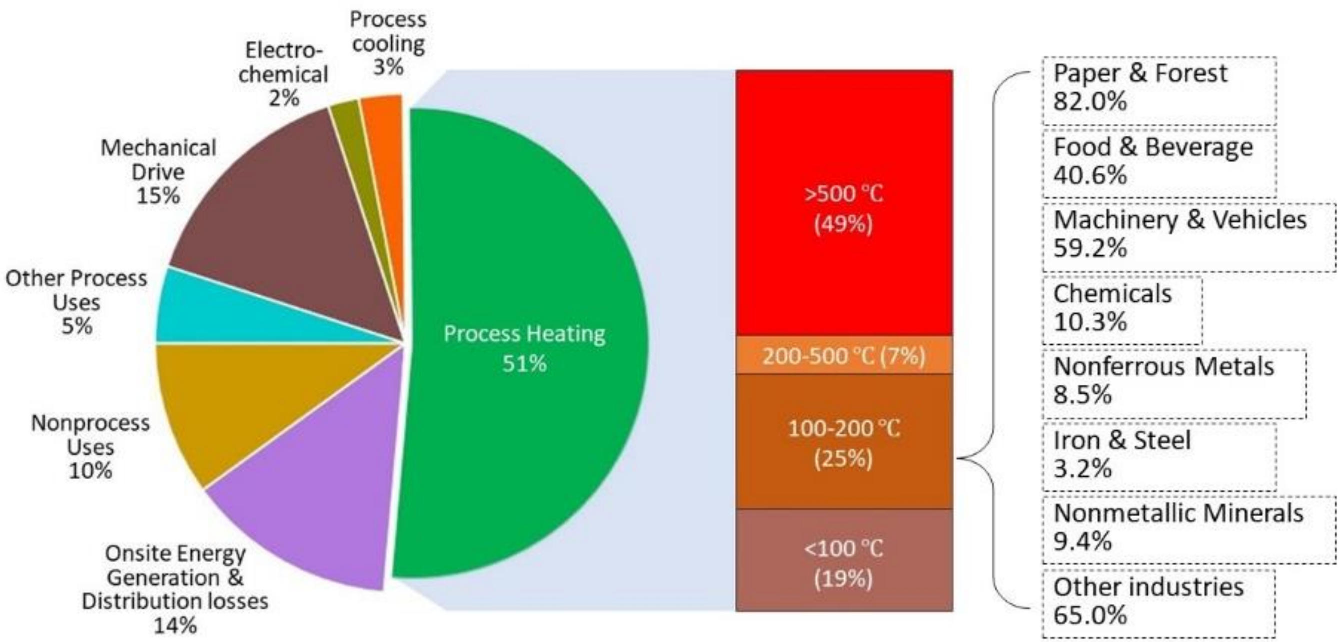
- HP for high energy efficiency
- State of the art: electric-driven mechanical vapor refrigerant compression cycles
- One of key technologies in industrial decarbonization

  Fossil fuels for 95% of process heating;

  Available waste heat (<100℃) in industry, e.g., paper drying;

  Technical feasibility of HTHPs for combined heating and cooling, e.g., food industry.

- R&D Efforts: advanced cycles and components, e.g., internal heat exchangers, two-phase ejectors.



Breakdown of on-site energy use and process heating temperature levels at US manufacturing facilities in 2018.*

*Manufacturing Energy and Carbon Footprint: All Manufacturing (2018 MECS)," U.S. Department of Energy Advanced Manufacturing Office, December 2021, https://www.energy.gov/sites/default/files/2022- 01/2018_mecs_all_manufacturing_energy_carbon_footprint.pdf.

Background

➢ *HTHPs using Two-Phase Ejector as an Expander*

- Basic configuration of HTHP
  Process: 1->2->3->4'->5'->1
- HTHP with a two-phase ejector
- Contributions of Ejector
  Expansion valve: $h_{4'} = h_{5'}$
  Ejector: $s_4 = s_5$
- Working principle of two-phase ejector
  Recovering energy from throttling loss, providing
  i. reduced compressor work,
  ii. increased specific cooling capacity.

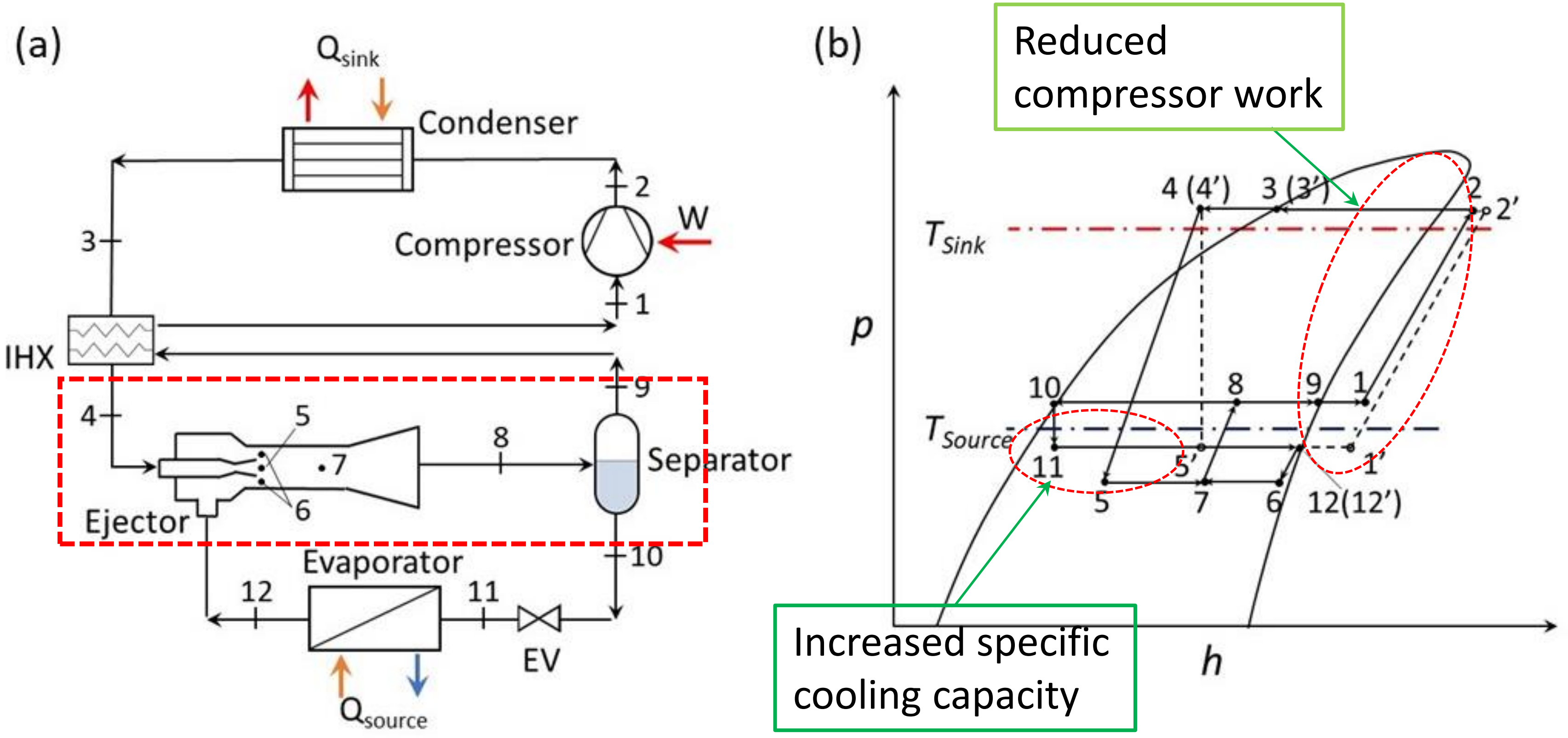


Fig. 1 HTHP with a two-phase ejector as an expander. (a) System configuration, and (b) P-h diagram.

Theoretical Model of Two-Phase Ejector

➢ *Two Types of Ejectors Used in HTHPs*

- Supersonic ejector: as a thermo-compressor in heat-driven HTHPs, Paper#938, #939 and #1133
- Two-phase ejector: as an expander replacing expansion valve, this study and Paper#459

  In subcritical cycle, high T/P liquid of primary fluid (PF) and low T/P vapor of secondary fluid (SF)

  In transcritical CO_2 cycle, high T/P vapor of PF and low T/P vapor of SF

➢ *Thermodynamic Model of Two-Phase Ejectors: Kornhauser's Model (1990)**

- Built with (1) the conservation of mass, momentum, (2) energy, constant-pressure mixing process,

  (3) homogeneous equilibrium model for thermodynamic quasi-equilibrium in two-phase flow
- Input: Properties of PF and SF, m_{PF}, T_4, P_4, T_{12}, and P_{12}; Ejector component efficiency, η_N, η_S, and η_D.
- Output: m_{SF} (or $\omega = m_{SF} / m_{PF}$), T_8, and P_8.
- Challenges: Guessed value of the mixing pressure, P_{mixing}.

  Kronhauser (1990): P_{mixing} for the same velocity of PF and SF before mixing;

  Lawrence and Elbel (2012)**: an equivalent temperature drop of 5 ℃ in the saturated pressure of SF.

*A. A. Kornhauser, "The use of an ejector as a refrigerant expander," presented at the International Refrigeration and Air Conditioning Conference, West Lafayette, IN, United States 1990, 82.
**N. Lawrence and S. Elbel, "Experimental investigation of a two-phase ejector cycle suitable for use with low-pressure refrigerants R134a and R1234yf," *International Journal of Refrigeration,* vol. 38, pp. 310-322, 2014/02/01/ 2014

Theoretical Model of Two-Phase Ejector

➢ *Gas-Dynamic Model of Two-Phase Ejectors (1)*

- Gas-dynamic process within an ejector

  i->ii->iii, PF accelerates in the primary nozzle, and creates low pressure zone at nozzle's outlet;

  iv->v, SF accelerates in the secondary nozzle;

  iii+v->vi, PF and SF mixes under p_{mixing};

  vi->vii, possible normal shock wave, if $M_{vi}>1$;

  vii->viii, mixed flow diffuses;

- Gas-dynamic model of a two-phase ejector

  A comprehensive, geometry-free, theoretical model;

  Homogeneous equilibrium in two-phase flow;

  Real properties of working fluids;

  Gas dynamic process depending on p_{mixing};

  Potential choked flow and normal shock wave is determined by the Mach number.

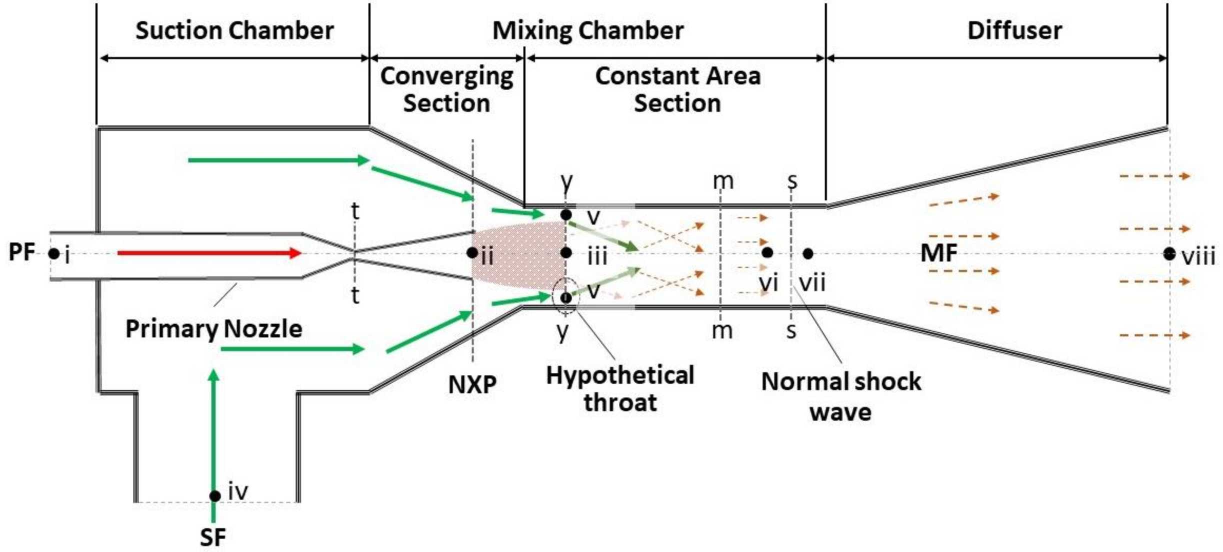


Fig. 2 Typical flow phenomena in a two-phase ejector. (NXP stands for nozzle exit plane. MF represents the mixed PF and SF)*

*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. Submitted to Energy.

Theoretical Model of Two-Phase Ejector

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➢ *Gas-Dynamic Model of Two-Phase Ejectors (2)*

- Governing equations

Energy conservation of PF through the primary nozzle,

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

For the SF flow, $h_{\text{v,is}} = h(s_{\text{iv}}, p_{\text{v}})$, and $V_{\text{v,max}} = C_{\text{v}}$.

In the mixing process, $p_{\text{iii}} = p_{\text{v}} = p_{\text{vi}} = p_{\text{M}}$,

$$\phi_{\text{M}}(\dot{m}_{\text{PF}} V_{\text{iii}} + \dot{m}_{\text{SF}} V_{\text{v}}) = (\dot{m}_{\text{PF}} + \dot{m}_{\text{SF}}) V_{\text{vi}},$$

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

For supersonic flow, $M_{\text{vi}} \geq 1$, condensation shock wave occurs.

For subsonic flow, $V_{\text{vii}} = V_{\text{vi}}$, $p_{\text{vii}} = p_{\text{vi}}$, and $s_{\text{vii}} = s_{\text{vi}} = s(p_{\text{vi}}, h_{\text{vi}})$.

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

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

and $x_{\text{viii}} = x(p_{\text{viii}}, h_{\text{viii}})$.

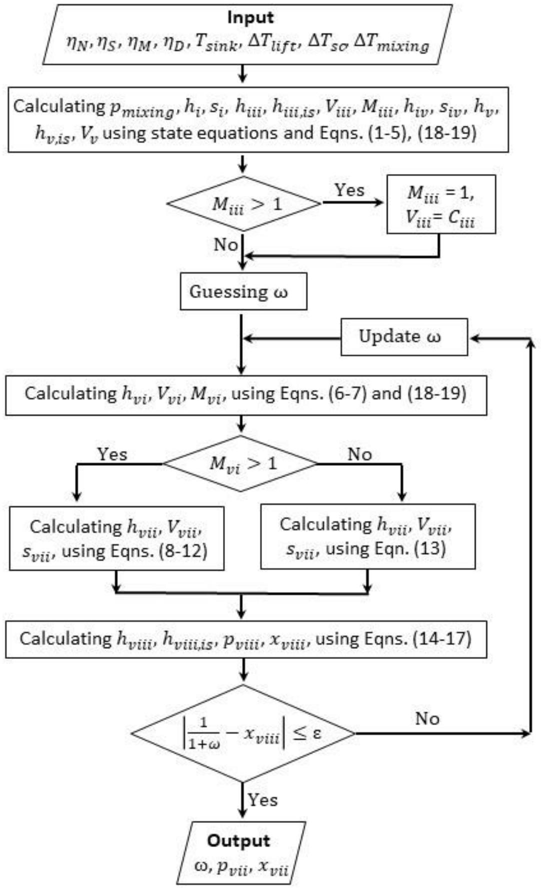


Fig. 3. Flow chart of solving the two-phase ejector model.

Model of HTHP with a Two-Phase Ejector

➢ *Model of HTHP with a Two-Phase Ejector*

A thermodynamic model is built with the mass and energy conservation in each component.

➢ *Performance of ejector-assisted HTHP*

Coefficient of Performance (COP): $COP_{\mathrm{EHTHP}} = \frac{Q_{\mathrm{sink}}}{W_{\mathrm{Comp}}}$

Volumetric Heating Capacity (VHC): $VHC = \eta_{\mathrm{vol}}\rho_1(h_2 - h_3)$

Ejector efficiency: $\eta_{\mathrm{EJT}} = \frac{W_{\mathrm{r}}}{W_{\mathrm{r,max}}} = \frac{h_{\mathrm{A}}-h_{\mathrm{B}}}{h_{\mathrm{C}}-h_{\mathrm{D}}}$

➢ *Low global-warming potential (GWP) refrigerants*

Group	Refrigerants	Formula	T_{cr} [°C]	P_{cr} [MPa]	ρ [kg/m³]	NBP [°C]	MW [kg/kmol]	ODP	GWP	SC
HC	R601	C_5H_{12}	196.6	3.37	10.1	36.1	72.2	0	5	A3
	R600	C_4H_{10}	152.0	3.80	25.2	-0.5	58.1	0	4	A3
HCFO	R1233zd(E)	$C_3ClF_3H_2$	166.5	3.62	34.8	18.3	130.5	0.00034	1	A1
	R1224yd(Z)	C_3ClF_4H	155.5	3.33	45.6	14.6	148.5	0.00012	<1	A1
HFO	R1336mzz(Z)	$C_4F_6H_2$	171.4	2.90	27.5	33.4	164.1	0	2	A1
	R1234ze(Z)	$C_3F_4H_2$	150.1	3.53	42.2	9.8	114.0	0	<1	A2L
HFC	R245fa	$C_3F_5H_3$	154.0	3.65	44.1	15.1	134.0	0	858	B1

Results and Discussions

- *Operating Parameters of HTHPs*
  - T_{sink} = 120 ℃, ΔT_{lift} = 40 ℃, ΔT_{sc} = 10 ℃, ΔT_{glide} = 0 ℃.
  - η_N = 0.8, η_S = 0.8, η_M = 0.9, and η_D = 0.8.
  - *Assumed ΔT_M,*

$$p_{mixing} = p_{sat}(T_{evap} - \Delta T_M)$$

- *Gas dynamic characteristics*
  - For an isentropic process, p_{mixing} ↓, Δh (enthalpy) ↑, x (quality) ↑, v_{PF}↑ and v_{SF}↑, but $v_{PF} > v_{SF}$; p_8 ↓.

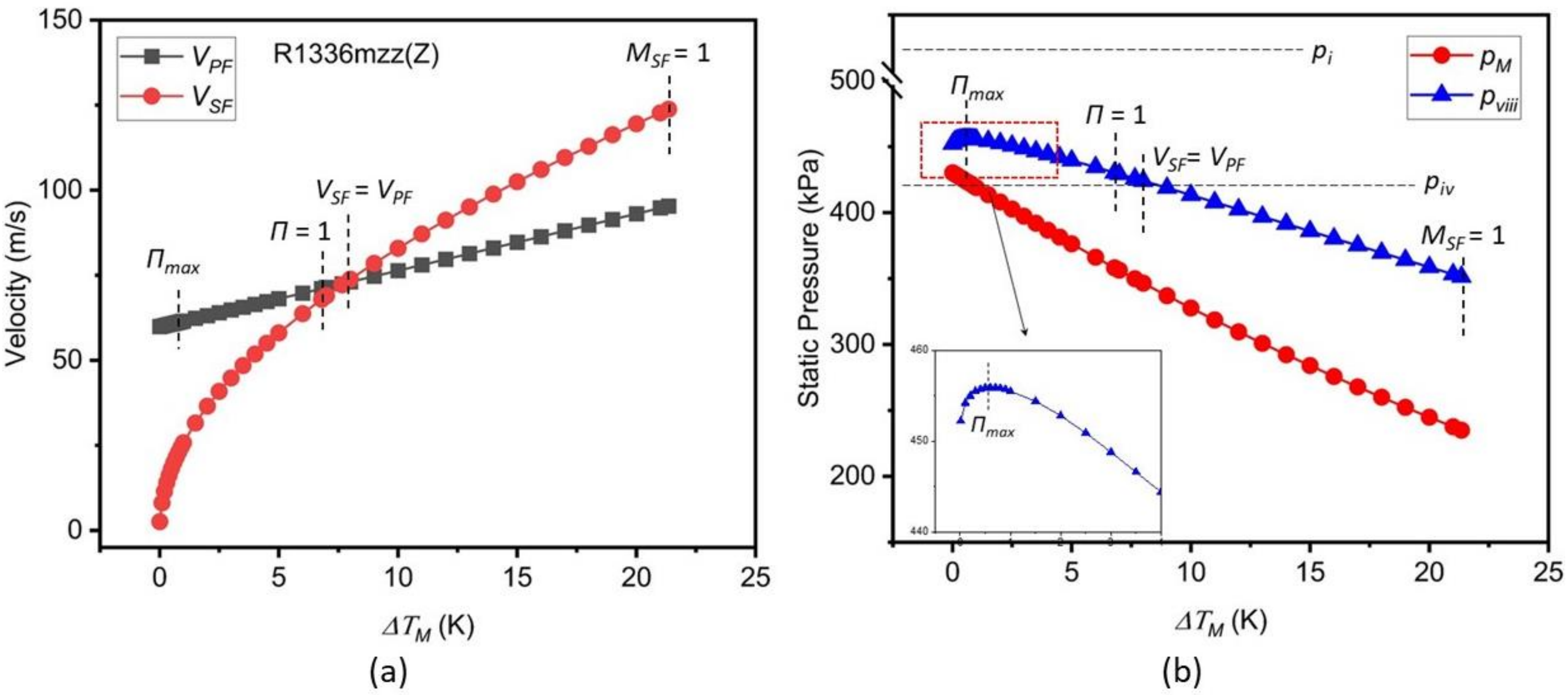


Fig. 4 Effects of the mixing pressure on the gas dynamic properties in a two-phase ejector. (a) Velocity, and (b) static pressure.

Results and Discussions

➢ *Effects of the Mixing Pressure (1)*

Four featured points: (1) max pressure lift ratio, Π_{max}; (2) no pressure lift ratio, $\Pi = 1$;
(3) zero mixing loss, $V_{PF} = V_{SF}$; (4) choked SF flow, $M_{SF} = 1$.

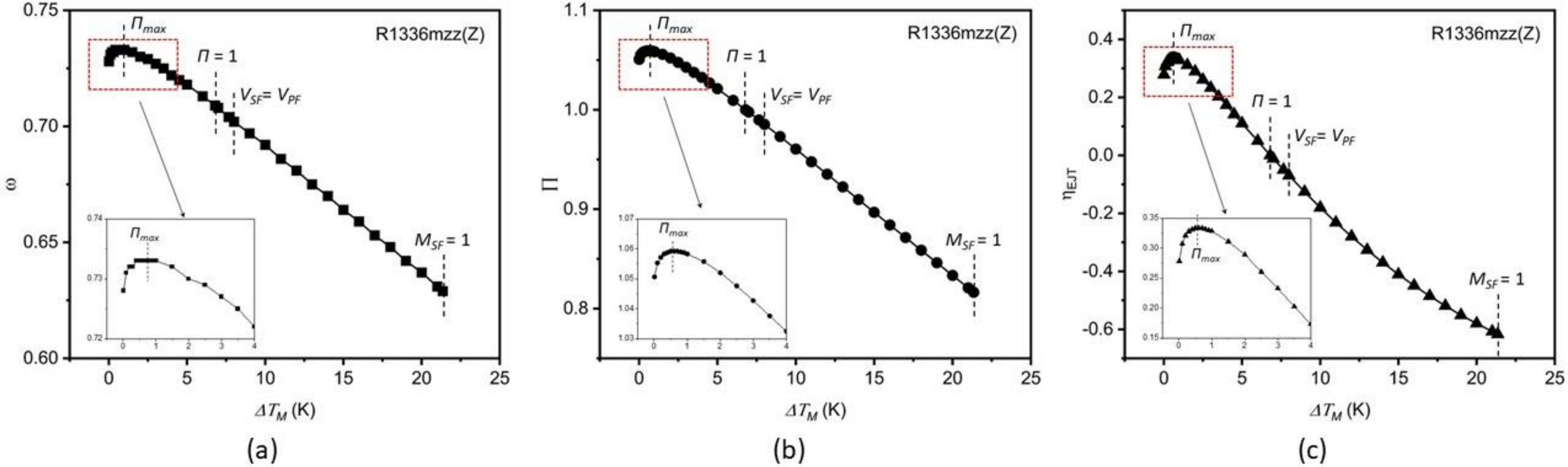


Fig. 5 Effects of the mixing pressure on the two-phase ejector's performance.
(a) Entrainment ratio, (b) pressure lift ratio, and (c) ejector efficiency.

Results and Discussions

- ***Effects of the Mixing Pressure (2)***
- COP and VHC of ejector-assisted HTHPs depend on the performance of two-phase ejector.
- p_{mixing} for the optimum η_{EJT} gives the maximum COP and VHC of HTHPs.

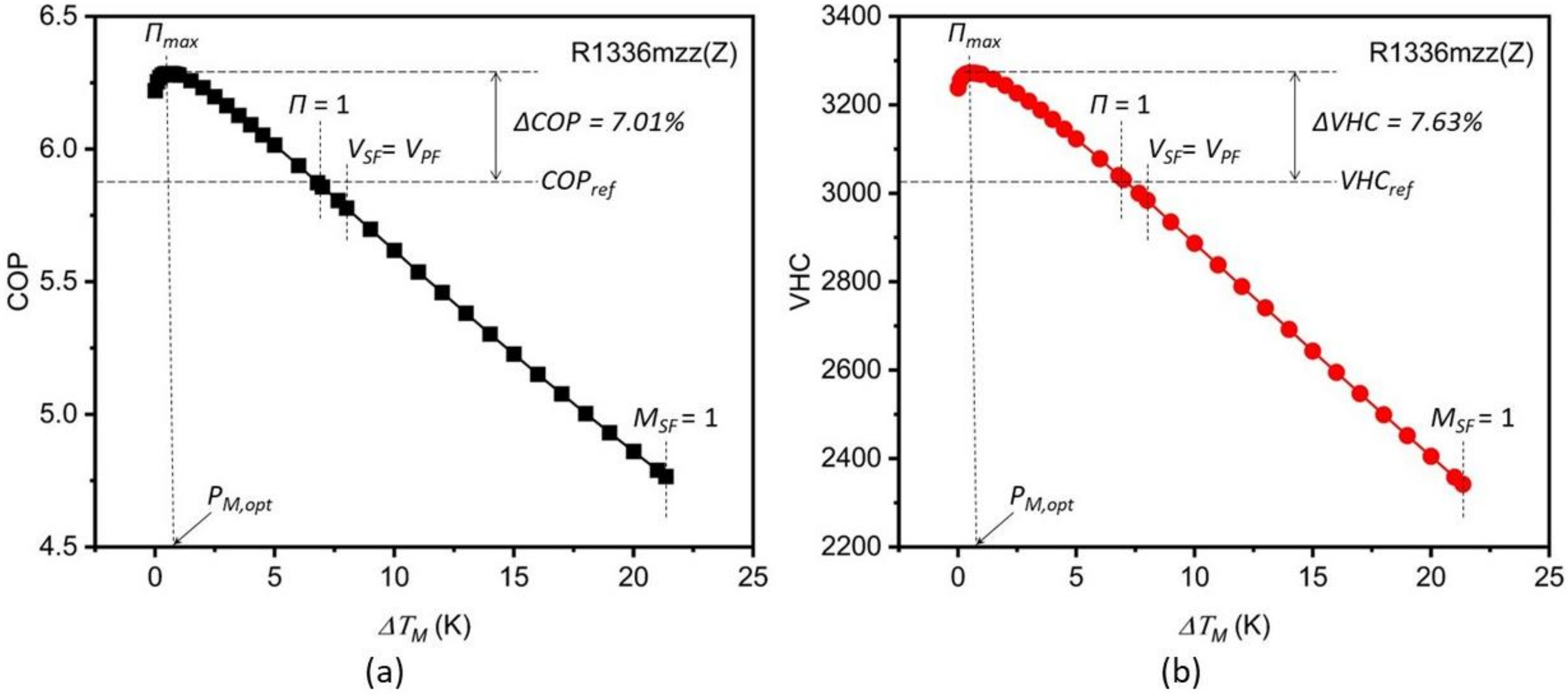


Fig. 6 Effects of the mixing pressure on the performance of an ejector-assisted HTHP.
(a) COP, and (b) VHC.

Results and Discussions

➢ *Effects of Working Fluids (1)*

- Averaged improvement ΔCOP = 7.2%±0.9%, ΔVHC = 7.3%±0.7% .
- A lower improvement in HTHPs, compared to trans-CO_2 HPs, ΔCOP = 15-30%.
- A smaller ΔT_{M}, ΔT_M = 0.7±0.1 ℃, compared to trans-CO_2 HPs, ΔT_M = 5 ℃.

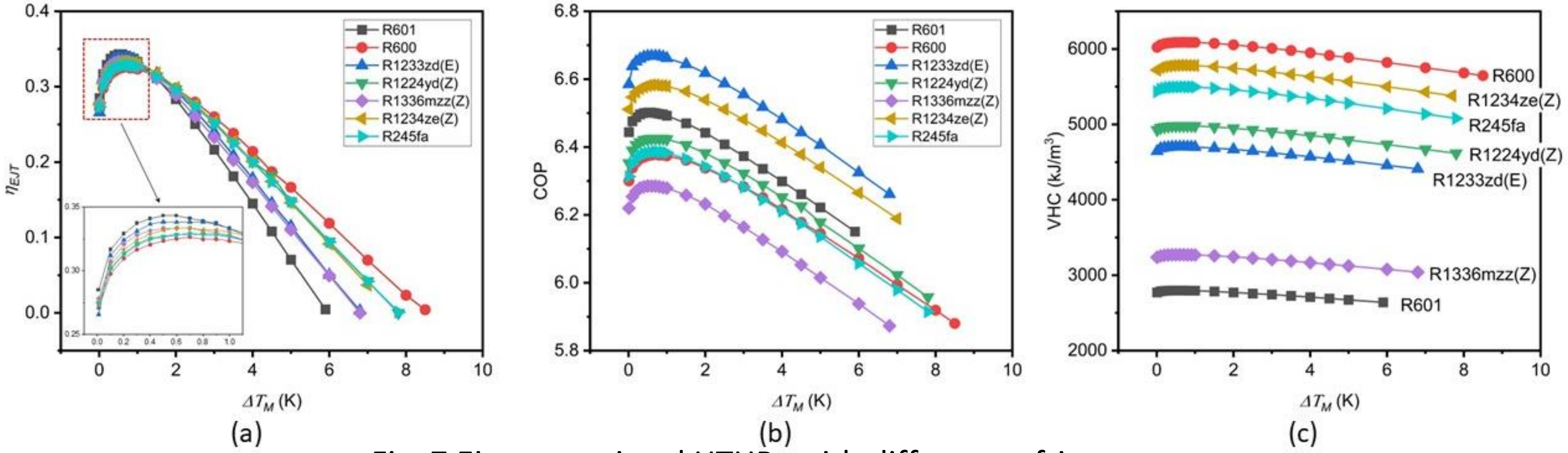


Fig. 7 Ejector-assisted HTHPs with different refrigerants.
(a) Ejector efficiency, (b) COP, and (c) ejector efficiency.

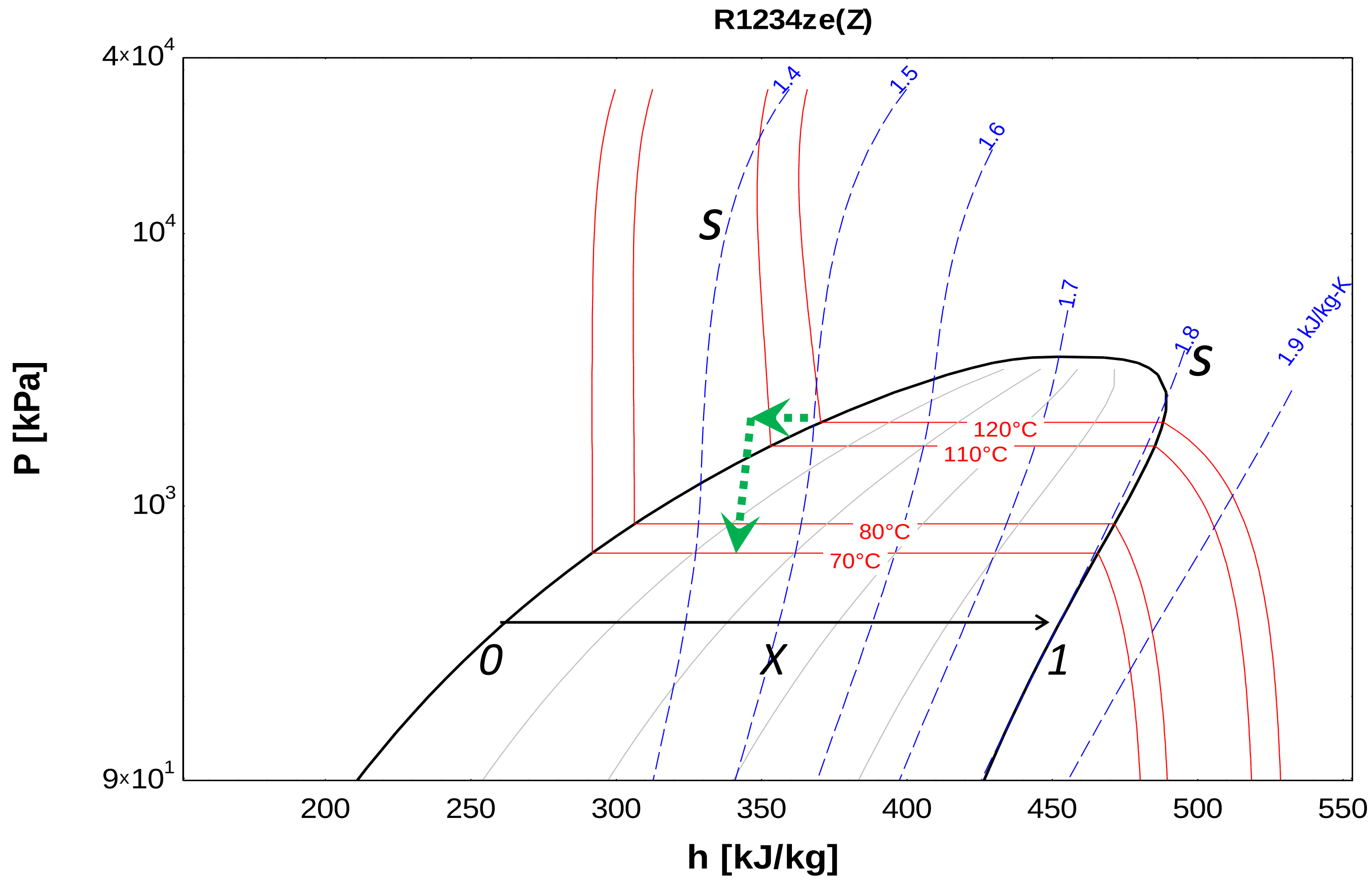
Results and Discussions

➢ *Effects of Working Fluids (2)*

- Thermal physical properties of refrigerants on HTHP's performance

(1) Primary fluid (PF) in low quality two-phase region, isentropic and isenthalpic lines are parallel, giving a low throttling loss;

(2) Secondary fluid (SF) in high quality two-phase region, slopes of isentropic lines are much larger than those of isenthalpic lines, giving a larger velocity increase.



P-h diagram of R1234ze(Z).

Conclusions and Future Work

Conclusions

- There is an optimum mixing pressure in a two-phase ejector, which gives the maximum performance of two-phase ejector and ejector-assisted HTHP.
- At the optimum mixing pressure, the two-phase flow in a two-phase ejector is subsonic. Choked flow of SF and condensation shock waves do not occur.
- The optimum mixing pressure of two-phase ejector for HTHPs is slightly lower than the evaporation pressure of SF.
- Two-phase ejector improves the performance of HTHPs with low GWP refrigerants. But the improvement of COP is less than these for transcritical CO_2 HPs.

Future work

- Design, fabricate, and experimental test of the component performance of two-phase ejector.
- Evaluate the system-level performance of HTHPs with a two-phase ejector, comparing with other energy recovery devices, e.g., turbo expanders, pressure exchangers, and vortex tubes.

Acknowledgement

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