



Searching for eco-friendly working fluids for ejector heat pump for domestic water heater

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Intro: Climate Change and Global Warming



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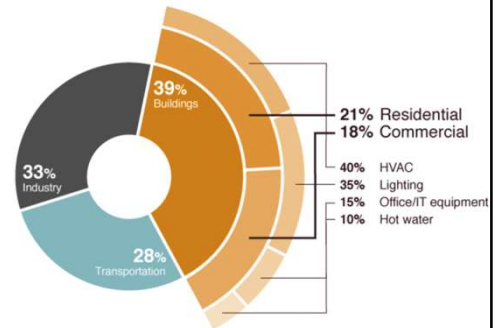
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Intro: Energy in the US Buildings

- ✓ U.S. residential and commercial buildings consume more than **one-third** of the produced energy.
- ✓ Roughly, buildings contribute by **35% (42 million metric tons)** in the carbon emissions each year.
- ✓ This is mainly because the current heat pump we use for cooling and heating is energy intensive and uses high GWP refrigerants, such as R134a (GWP = 1,430).



How we can cool, heat, and ventilate our buildings more efficiently with low emissions?

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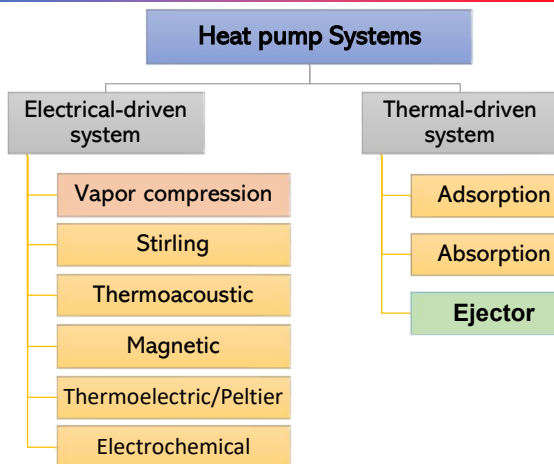
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<https://www.weforum.org/agenda/2022/10/here-s-how-heat-ventilate-cool-buildings-energy-consumption/>

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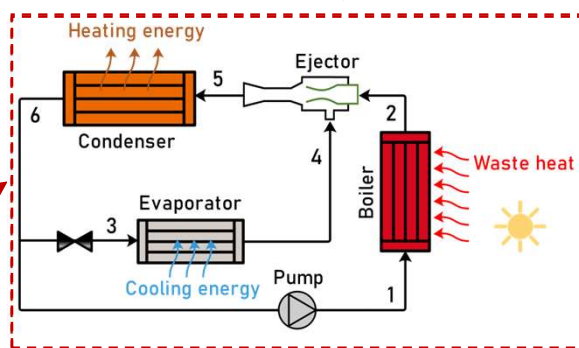


Intro: Heat Pump – State-of-the-Art



✓ Advantages:

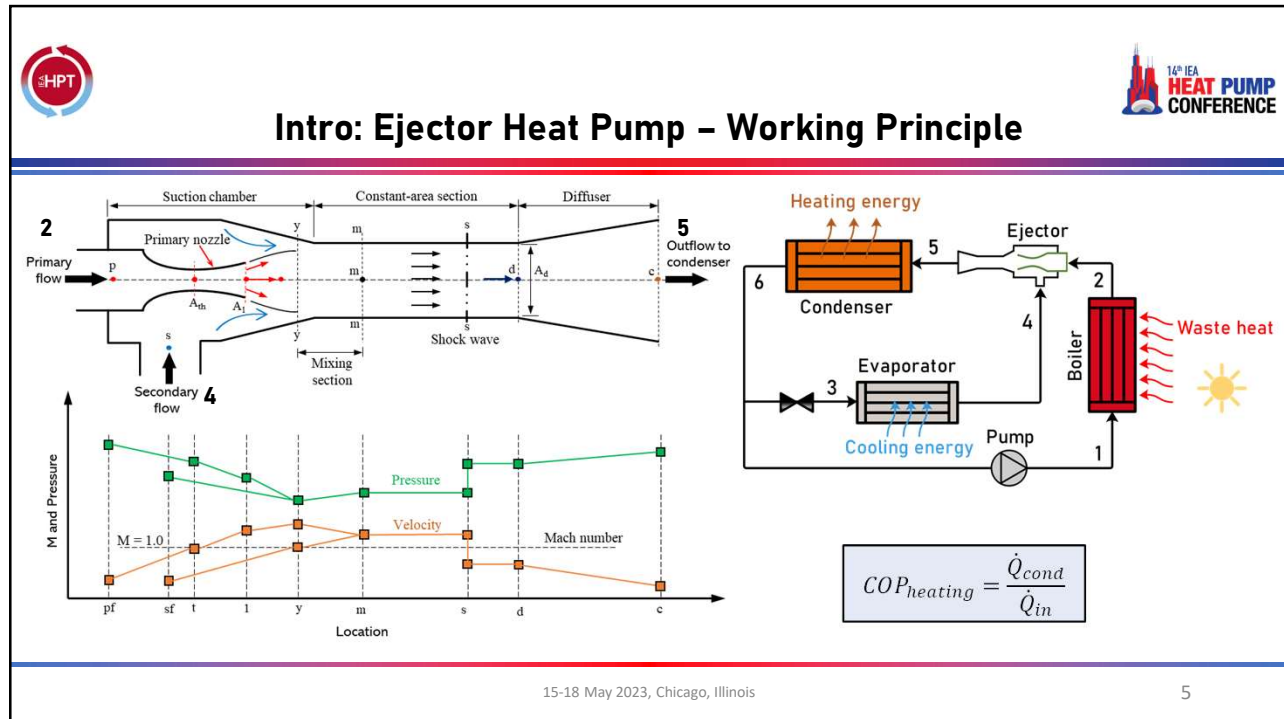
It is simple design, has no moving parts, has low maintenance, uses eco-friendly working fluids.



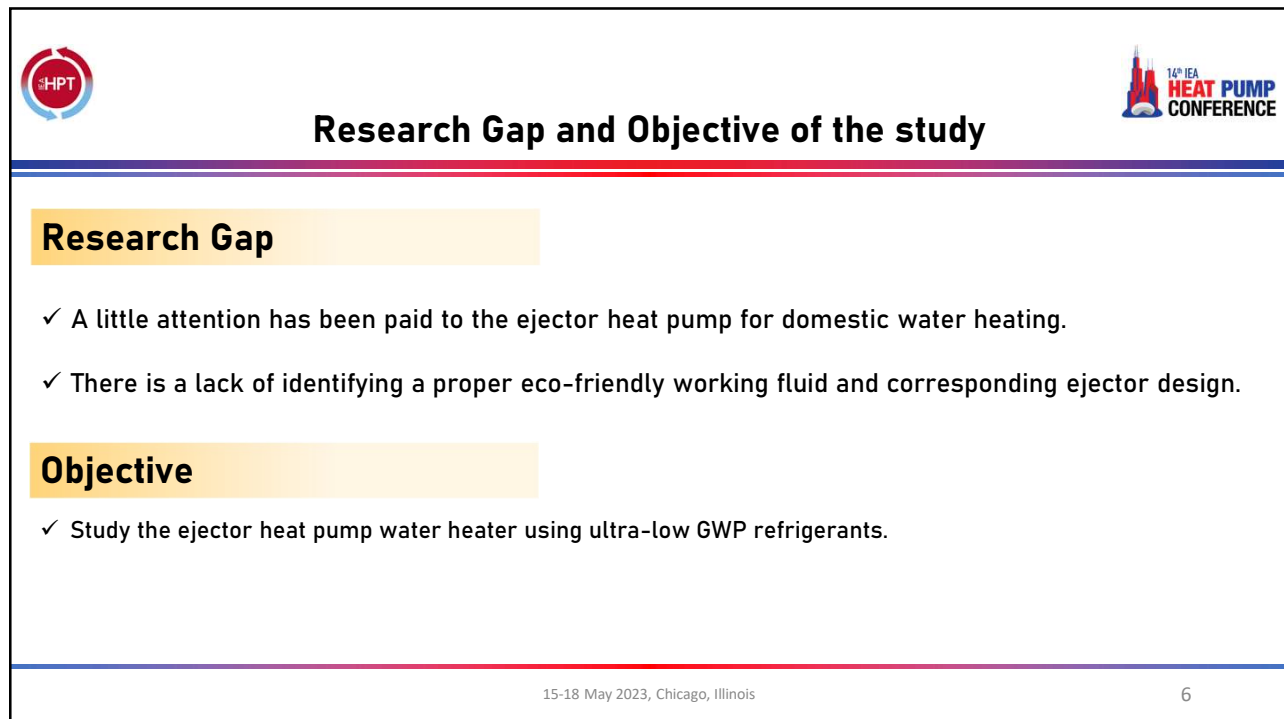
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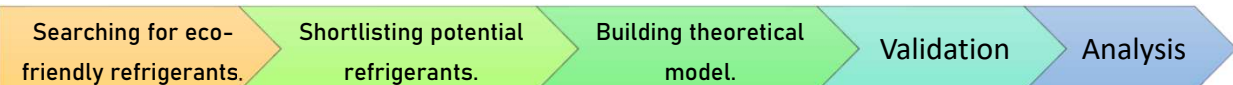
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Research Methodology



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Selected refrigerants with low GWP and zero ODP

	Refrigerants	P_{sat}^* [bar]	T_{cr} [°C]	P_{cr} [bar]	NBP [°C]	γ	MW [kg/kmol]	ODP	GWP (AR4)	SC
Under vacuum	R1336mzz(Z)	0.475	171.3	29	33.5	1.074	164.1	0	2	A1
	R601a	0.620	187.2	33.7	27.9	1.092	72.15	0	4	A3
	R1233zd(E)	0.871	165.6	35.73	18.3	1.105	130.5	0	1	A1
	R1224yd(Z)	0.98	155.5	33.37	14.6	1.104	148.5	0	< 1	A1
Above atmospheric	R1234ze(Z)	1.21	150.1	35.31	9.7	1.133	114	0	7	A2L
	R600a	2.54	134.7	36.4	-11.7	1.139	58.12	0	< 5	A3
	R1234ze(E)	3.59	109.4	36.32	-19.3	1.15	114	0	7	A2L
	R1234yf	5.01	94.7	33.82	-29.5	1.177	114	0	< 5	A2L
	R290	7.20	96.68	42.47	-42.1	1.251	44.1	0	< 5	A3
	R1270	8.80	92.42	46.65	-47.7	1.303	42.08	0	2	A3

* Pressure calculated at 14.4 °C.

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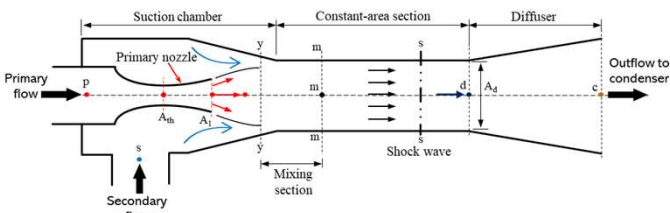
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Theoretical Model



Component	Governing equations	Eq.
Primary nozzle	$\dot{m}_{pf} = \frac{P_g A_{th}}{\sqrt{T_g}} \sqrt{\frac{\gamma}{R} \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}} \sqrt{\eta_{pn}}}$	(1)
	$\frac{A_1}{A_t} \approx \frac{1}{M_{p1}} \left[\frac{2}{\gamma+1} \left(1 + \frac{\gamma-1}{2} M_{p1}^2 \right) \right]^{\frac{\gamma+1}{2(\gamma-1)}}$	(2)
	$\frac{P_g}{P_{p1}} \approx \left(1 + \frac{\gamma-1}{2} M_{p1}^2 \right)^{\frac{\gamma}{\gamma-1}}$	(3)
Secondary nozzle (Suction chamber)	$\dot{m}_{sf} = \frac{P_e A_{sy}}{\sqrt{T_e}} \sqrt{\frac{\gamma}{R} \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}} \sqrt{\eta_{sn}}}$	(4)
	$\frac{A_{py}}{A_1} = \frac{\phi_p M_{p1}}{M_{py}} \left[\frac{1 + \frac{\gamma-1}{2} M_{py}^2}{1 + \frac{\gamma-1}{2} M_{p1}^2} \right]^{\frac{\gamma+1}{2(\gamma-1)}}$	(5)
	$\frac{P_e}{P_{sy}} \approx \left(\frac{\gamma+1}{2} \right)^{\frac{\gamma}{\gamma-1}}$	(6)

Continuity, momentum, and energy conservation equations.



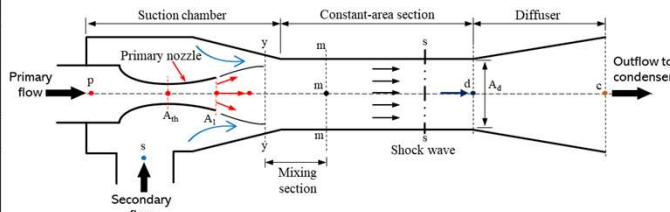
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Theoretical Model

Component	Governing equations	Eq.
Mixing chamber	$\frac{P_{py}}{P_{p1}} \approx \left(\frac{1 + \frac{\gamma-1}{2} M_{p1}^2}{1 + \frac{\gamma-1}{2} M_{py}^2} \right)^{\frac{\gamma}{\gamma-1}}$	(7)
	$\phi_m (\dot{m}_p u_{py} + \dot{m}_s u_{sy}) = (\dot{m}_p + \dot{m}_s) u_m$	(8)
	$\dot{m}_{pf} \left(h_{py} + \frac{u_{py}^2}{2} \right) + \dot{m}_{sf} \left(h_{sy} + \frac{u_{sy}^2}{2} \right) = (\dot{m}_{pf} + \dot{m}_{sf}) \left(h_m + \frac{u_m^2}{2} \right)$	(9)
Normal shock	$\frac{P_d}{P_m} = 1 + \frac{2\gamma}{\gamma+1} (M_m^2 - 1), M_d^2 = \frac{1 + \frac{\gamma-1}{2} M_m^2}{\gamma M_m^2 - \frac{\gamma-1}{2}}$	(10)
Diffuser	$\frac{P_c}{P_d} = \left(1 + \frac{\gamma-1}{2} M_d^2 \right)^{\frac{\gamma}{\gamma-1}}$	(11)



Ejector model is coupled with the HP model to estimate the COP

$$COP = \frac{\dot{Q}_{cond}}{\dot{Q}_{boiler}} = 1 + \frac{\dot{m}_{sf}}{\dot{m}_{pf}} \times \frac{h_v|_{T_e} - h_l|_{T_c}}{h_v|_{T_g} - h_l|_{T_c}}$$

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Code Validation

Table 2. Comparison between present results and previous experimental data for ejector heat pump.

T_{boiler} (°C)	Previous results [3]	Present model	Error (%)
120	0.6849	0.6615	3.42
125	0.6074	0.5864	3.45
130	0.5299	0.5158	2.66
135	0.4544	0.4671	2.79
140	0.3822	0.3920	2.56

✓ The max relative error was less than 4%, indicating the model is valid to model EHPWH.

[3] [https://doi.org/10.1016/0140-7007\(95\)98160-M](https://doi.org/10.1016/0140-7007(95)98160-M)

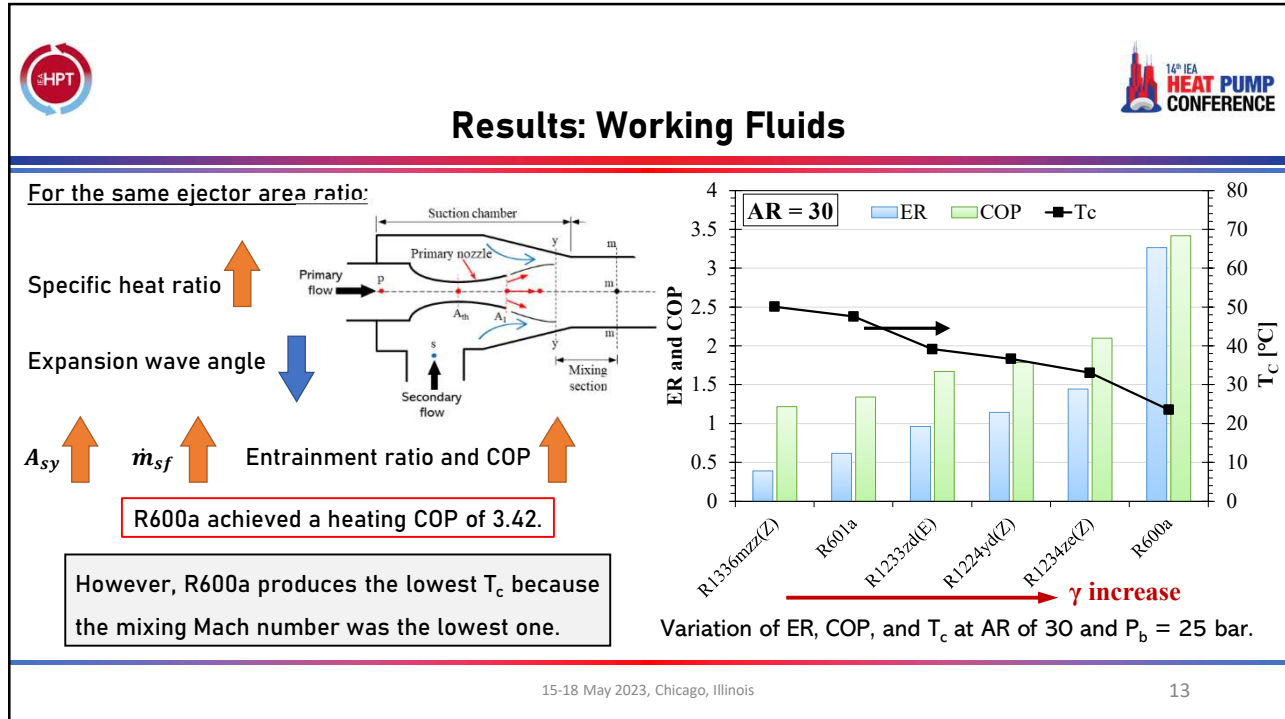
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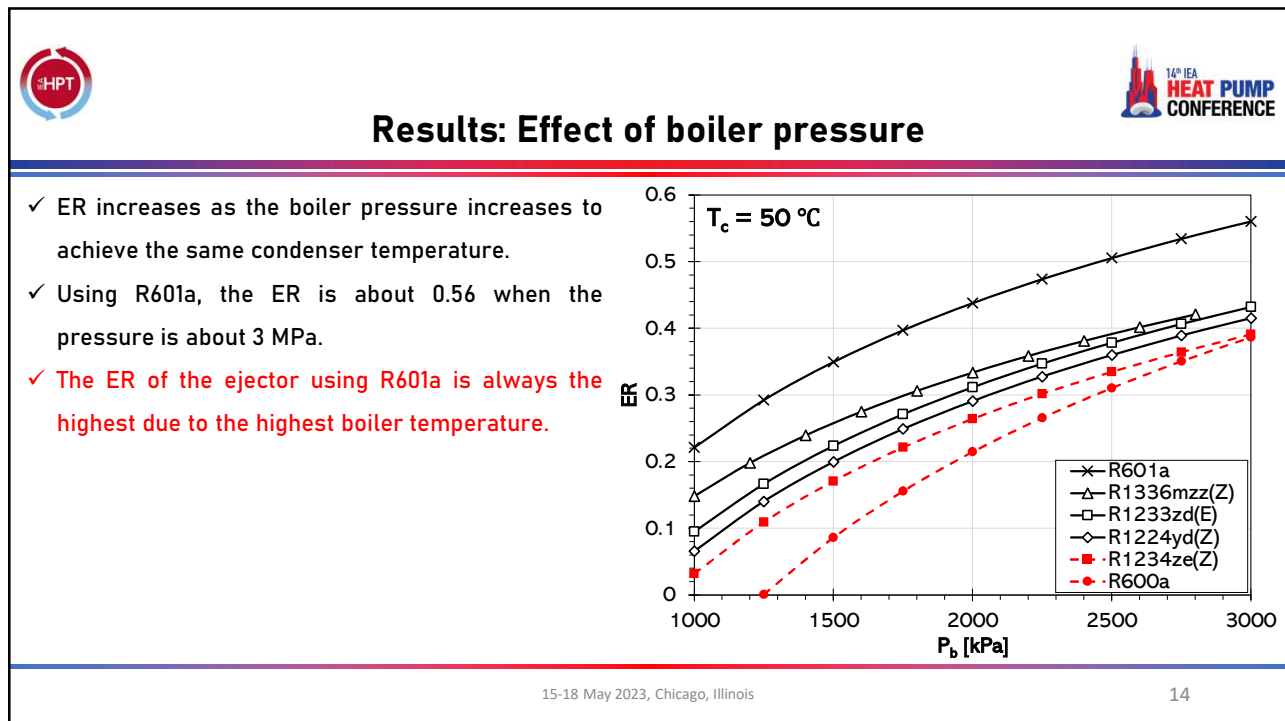
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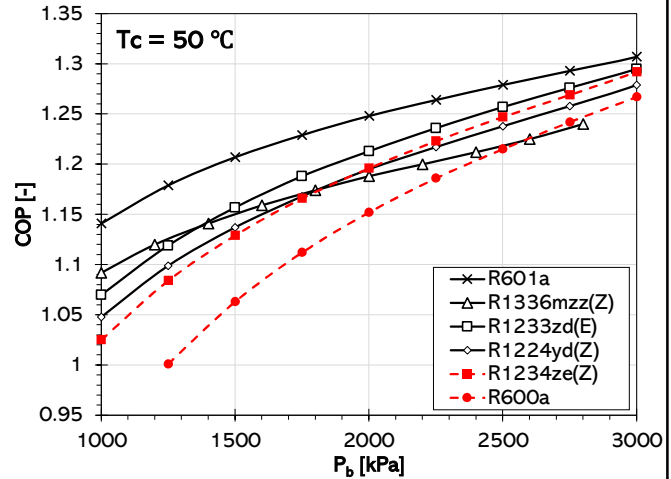


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Results: Effect of boiler pressure

- ✓ The COP profiles follow the same trends as ER.
- ✓ Interestingly, the COP of cycle using R1234ze(Z) rapidly increases and approaches the COP of R601a when the boiler pressure increases.
- ✓ This behavior is due to the shape of the saturation curve (P-h diagram) of R1234ze(Z), where h_{fg} significantly decreases as the pressure increases, and hence the heat added in the boiler decreases, leading to a remarkable increase in the COP.
- ✓ So, the highest ER does not always correspond to the highest COP.



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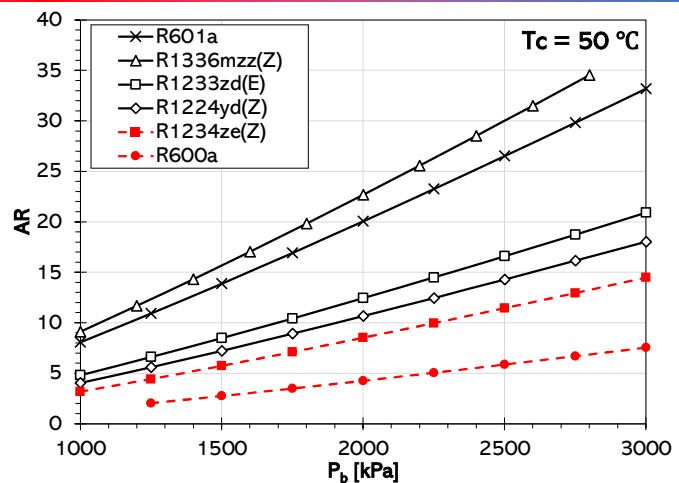
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Results: Effect of boiler pressure

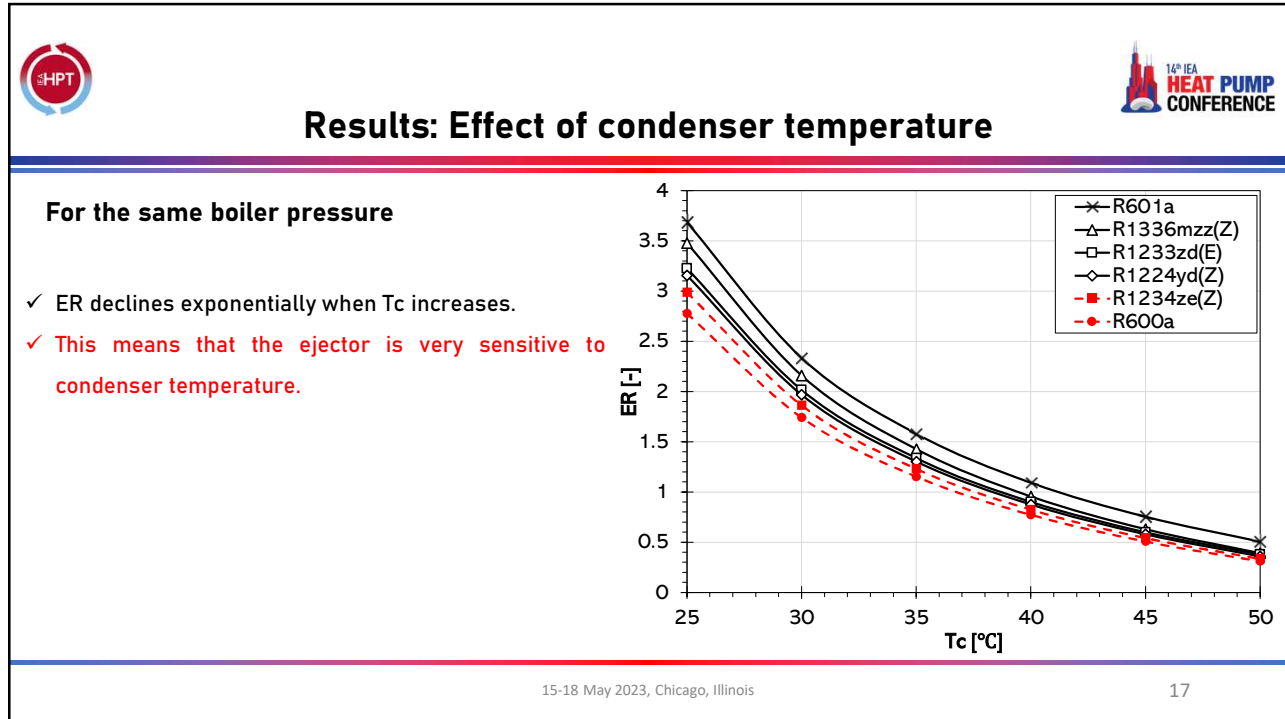
- ✓ The area ratio does not follow the ER and COP trends.
- ✓ To achieve the same condenser pressure, the ejector area ratio should be high for working fluid with higher molecular weight.
- ✓ Because R1336mzz(Z) has the highest value of the molecular weight, the ejector area ratio is the highest.



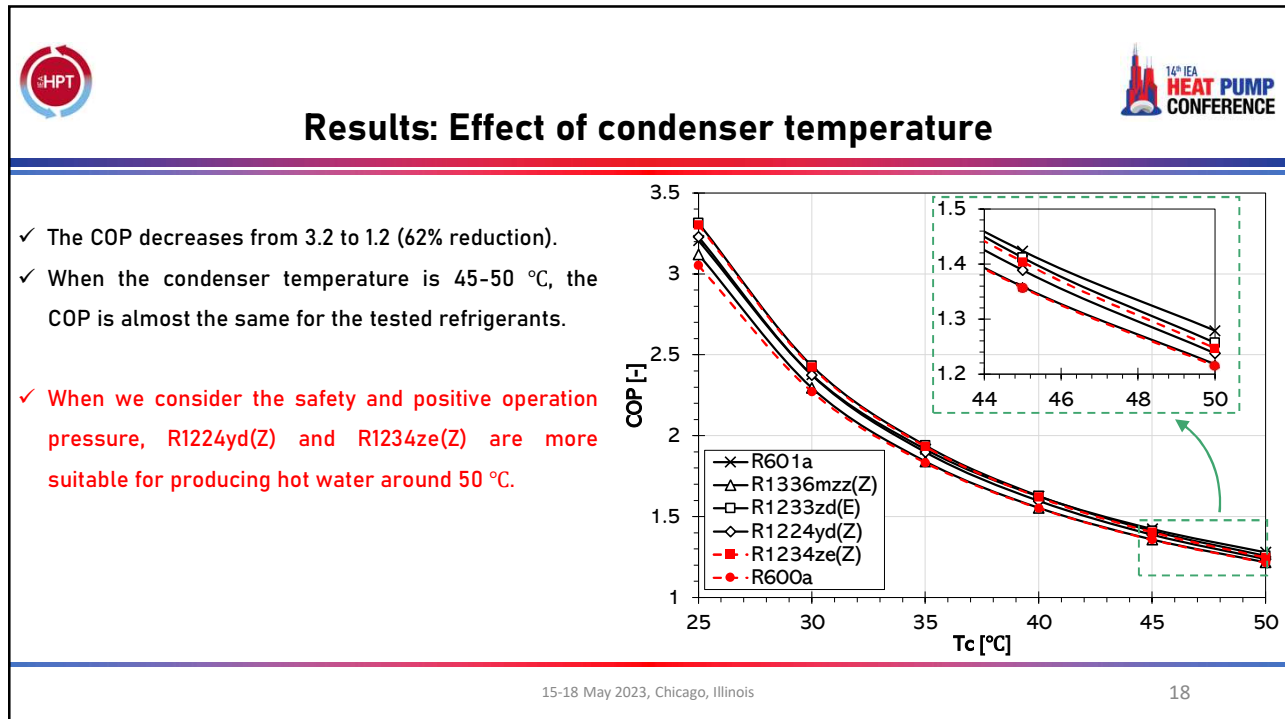
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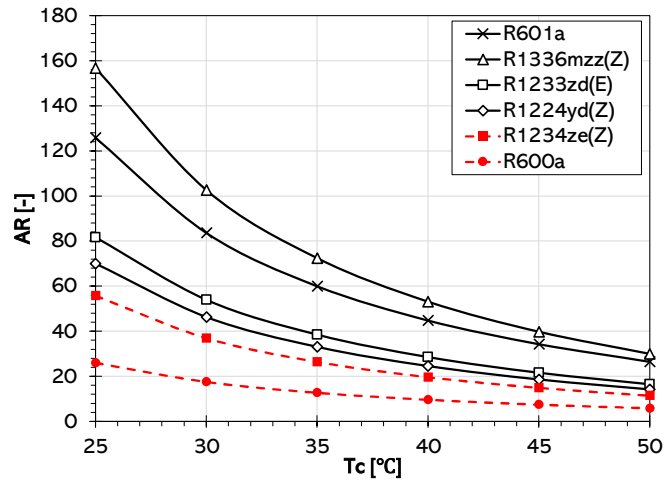


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Results: Effect of condenser temperature

- ✓ Again, a refrigerant with a higher molecular weight needs a bigger ejector to be able to achieve the desired condenser temperature.
- ✓ The AR decreased by about 80% when the T_c changes from 25 to 50 °C.
- ✓ This means that the ejector should be designed for a specific condenser pressure.



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Conclusion

- Higher ER does not always guarantee higher COP due to the shape P-h diagram.
- The COP is very sensitive to the condenser temperature. Thus, the ejector should be designed for specific operating conditions to be able to achieve high performance.
- Under vacuum: R601a and R1233zd(E) achieve the highest COP at any condenser temperature.
- Above vacuum: R1224yd(Z) and R1234ze(Z) are preferable for providing hot water at 50 °C.

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Thank You



Q & A

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