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Effect of Fractionation on Ejector and System Performance in R1234yf/R32 Refrigeration System

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ABSTRACT

The fractionation and the composition shift in the zeotropic refrigerant systems adds complexity in their design. Though several studies have shown that the zeotropic refrigerants can improve the system performance of a conventional refrigeration cycle, its impact on an ejector system performance has not been studied systematically. This study numerically investigates two different ejector systems along with a baseline system to understand if the fractionation can improve the performance of system that employs R1234yf/R32 zeotropic mixture as working fluid. The study first introduces the modeling approaches employed to model system components like ejector, heat exchangers, compressor, and separator with fractionation. The performance of the ejector is predicted using the Kornhauser model while considering three different refrigerant mixture compositions at the motive inlet, the suction inlet, and the diffuser exit. The heat exchangers are modeled using harmonic weighted LMTD method, while the variable speed compressor is modeled using ten-coefficient polynomials. For system level investigation, a baseline system model working on a conventional vapor compression cycle is developed in MATLAB. It is assumed that there is no composition shift due to the differential hold up inside the microchannel heat exchangers and the connecting pipes. The first investigated ejector system is working on a standard ejector cycle (SEC) and has a separator in the cycle layout. The fractionation effects that cause high-volatile substance rich composition to move through the high-side and low-volatile substance rich composition to move through the low-side of the cycle, are present in the SEC system due to the separator. The fractionation inside the separator is predicted under uniform pressure and temperature assumption. The second ejector system is working on a condenser outlet split (COS) cycle which employs a receiver. Thus, it is assumed that there are no fractionation effects in the COS system. The study reports that for an ejector as a component, the fractionation improves its performance. The study evaluates the ejector performance with a composition shift at the motive and the suction port for R454B and R454C. It is predicted that the ejector efficiency increases by 7% for an equal composition shift scenario for both the refrigerant mixtures. However, the study also finds that the gain in the ejector performance due to fractionation couldn't translate into an increase in the system COP for the matched capacity conditions. The SEC system's COP decreases by -3% with fractionation for the composition with the maximum temperature glide. However, a gain of 45% in the COP is predicted for a hypothetical scenario of no fractionation for the same composition. Similarly, in the COS system with no fractionation effects, a 10% gain in COP is predicted for the mass entrainment ratio that has the highest COP. These numerical calculations are crucial to set the direction of future experimental studies where the ejector cycle architectures that avoid fractionation inside the separator like the COS cycle, should be investigated.

1. INTRODUCTION

The zeotropic mixtures gained attention in search of finding alternatives to CFCs. The studies have shown that the zeotropic mixtures can either be used for improving the energy efficiency (Mulroy et al., 1988) or for the capacity modulation (Kim et al., 2004). The zeotropic mixtures are known for their temperature glide during the phase change process which can improve the heat transfer with the heat transfer fluid (HTF), which usually gain or lose heat through a sensible process. In the light of recent F-gas regulations, the HVAC&R industry is searching for appropriate low-GWP refrigerants. The zeotropic mixtures of R1234yf and R32 like R454B and R454C are receiving special attention due to their low-GWP.

Ejector, as a work recovery device has also received attention in the last few decades. Over years, it has gained importance particularly for the CO_2 systems as they have large throttling losses (Elbel and Hrnjak, 2008). However, studies have shown that the ejector can improve performance of other low-pressure refrigerants as well like R1234yf and R134a (Lawrence and Elbel, 2014), and R410A (Lawrence and Elbel, 2016). The literature suggests that different ejector cycle layouts like the standard ejector cycle (SEC), condenser outlet split (COS) cycle, diffuser outlet split cycle, and liquid recirculation cycle can be used.

Even though, zeotropic mixtures have been studied for conventional vapor compression system, there has been no systematic study for evaluating performance of the zeotropic mixture for the systems employing ejector as a work recovery device. One interesting aspect of investigating the zeotropic mixtures for an ejector system is the effect of fractionation on the system performance. The fractionation is the difference in the composition of the vapor and the liquid phase for a zeotropic mixture when subjected to phase separation. The vapor phase becomes rich in the high-volatile substance, whereas the liquid phase becomes rich in the low-volatile substance. The standard ejector cycle, one of the widely studied ejector cycles, employs a separator. This means that due to fractionation inside the separator, the high-volatile substance rich composition will be circulating in the high-side of the system, whereas low-volatile substance rich composition will be circulating on the low-side of the cycle. Thus, it will be interesting to study the effects of fractionation inside the separator on the ejector systems performance.

This study is organized into two sections. The first section introduces the modeling methodology for different components of the refrigeration system. These include the ejector, the heat exchangers (evaporator and condenser), and the compressor. Then, the study introduces three different system layouts. The first system is the baseline system working on a conventional vapor compression system. The second is an ejector system working on a standard ejector cycle (SEC) with fractionation inside the separator. The third, is the second ejector system working on a condenser outlet split (COS) cycle which has a receiver, instead of a separator and thus, allows the same circulating composition within the system. The second section discusses the key findings of the study. At first, the study presents the effect of composition shift at the motive and the suction inlets for R454B and R454C refrigerant mixtures. Then, the study presents the system level simulation results for the above mentioned three systems. The study discusses the effects of fractionation on the performance of the ejector systems.

2. NUMERICAL MODELING/METHODOLOGY

2.1 Component modeling

2.1.1 Ejector model

The ejector is modeled using Kornhauser (1990) model. The flowchart of the model solver is shown in Figure 1. The model needs three different part efficiencies namely, the motive nozzle efficiency η_{mn}, the suction nozzle efficiency η_{sn}, and the diffuser efficiency η_d. It is assumed that all the three efficiencies are equal to 0.7. The model also requires setting up the mixing pressure P_{ms}. It is assumed that P_{ms} is the saturated pressure corresponding to the mixing temperature T_{ms} such that T_{ms} is lower by 2°C than the suction inlet temperature T_{sn} i.e., $\Delta T_{ms} = T_{sn} - T_{ms} = 2^{\circ}\mathrm{C}$. Moreover, the model can handle not only pure refrigerant, but also a zeotropic mixture refrigerant with different compositions at the motive and the suction inlets. For pure refrigerant all the equations involving different parts of ejector are solved assuming same composition of the working fluid. However, in the case of a zeotropic mixture, the composition of the motive inlet, the suction inlet and the diffuser can be different and can be assigned by specifying the mass composition of the high-volatile substance. The ejector performance is reported using the mass entrainment ratio, the pressure lift, and the ejector efficiency (Elbel and Hrnjak, 2008).

2.1.2 Heat exchanger model

The heat exchangers could be modeled with different level of fidelities. Finite volume-based approach can give the most accurate heat exchanger performance prediction; however, a simpler heat exchanger model may suit better while exploring the potential performance gain in the system performance using the ejector and the zeotropic refrigerant mixture. Therefore, the harmonic weighted LMTD method (Domanski and McLinden, 1992) is utilized in this study. In this method, LMTD is expressed as a harmonic mean weighted with the fraction of heat transferred in individual sections of the heat exchanger as shown in Equation (1).

$$\frac{1}{LMTD_{hx}} = \frac{1}{\dot{Q}_{hx}} \sum \frac{\dot{Q}_i}{LMTD_i} \tag{1}$$

Q_i is obtained by dividing each heat exchanger zones (single and two phase) into multiple parts while assuming a counterflow arrangement. This methodology can account any nonlinear temperature profiles in the heat exchangers that arises due to the temperature glide of the zeotropic mixtures. It assumes that the overall heat transfer coefficient U is same for both the two-phase and the single-phase zones (superheated vapor or subcooled liquid). Though this assumption may not hold true in the physical system as the heat transfer coefficient may change significantly as the refrigerant flows in different zones. However, this assumption is considered in the study for modeling both the evaporator and the condenser.

Another important aspect in modeling of heat exchangers involving the zeotropic mixture is to select method of comparing different systems with respect to the choice of reference temperature (McLinden and Radermacher, 1987). In this study, the inlet and exit conditions of Heat Transfer Fluid (HTF) are specified and have been kept constants for all the system studies. The HTF conditions for condenser are kept at $T_{in} = 35$°C and $T_{out} = 43.2$°C, whereas for evaporator, the HTF conditions are specified as $T_{in} = 26.7$°C and $T_{out} = 14.4$°C. The UA value for evaporator is 0.3kW/°C, whereas it is 0.4 kW/°C for the condenser.

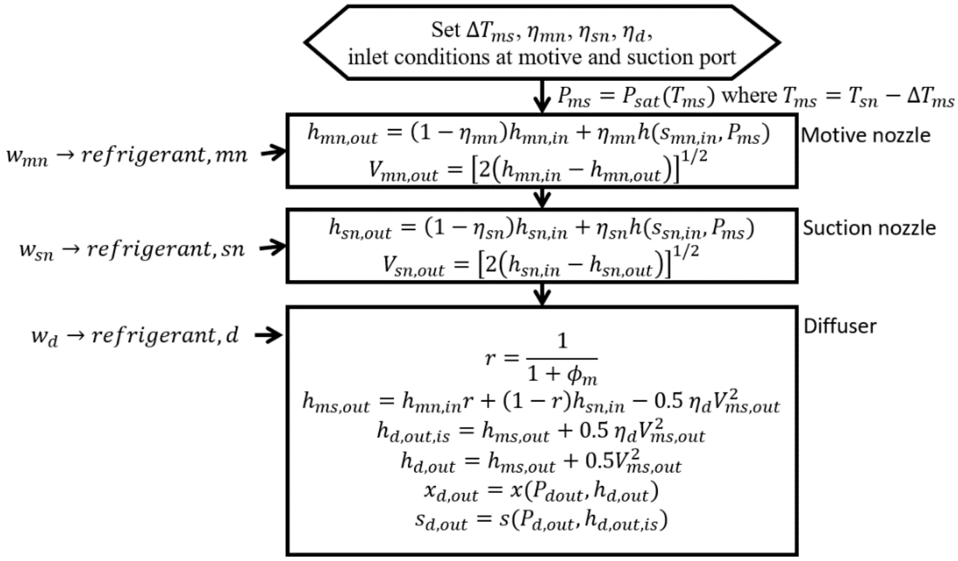


Figure 1 Flowchart of the ejector model calculations

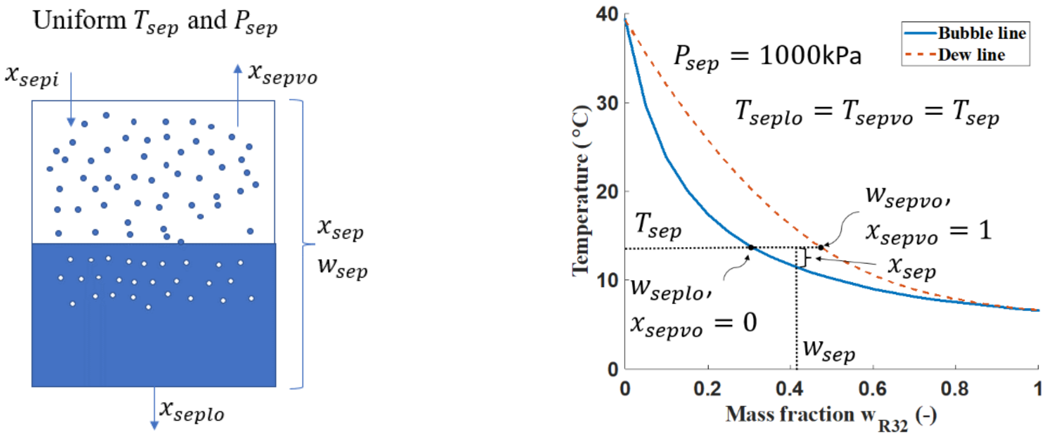
2.1.3 Compressor model

A realistic compressor model is important to study the potential of an ejector system as the ejector aims to unload the compressor by allowing start of the vapor compression process at relatively higher pressure. This typically results in lower compressor speeds and higher COP for the matched capacity case. In this study, two different compressor models are utilized. The compressor is modeled using a constant compression efficiency $\eta_{comp} = 0.7$ in section 3.2 where the baseline system model developed in MATLAB is compared with NIST's Cycle_D-HX model (Brignoli et al., 2017). In rest of the paper, a variable speed compressor model is used where the performance data for each of the two compressor efficiencies (η_{comp}, η_{vol}) is curve-fitted using 10-coefficient polynomials (Haider and Elbel, 2020). The performance data for each of the two compressor efficiencies is generated while keeping typical trends observed in the experimental performance of compressor. Like, the compression efficiency η_{comp} is higher at a particular pressure ratio ($\Pi = 2$) and the rated speed ($\text{N} = 2800 min^{-1}$). If either the pressure ratio or compressor speed changes (increases/decreases), the η_{comp} drops. Similarly, the η_{vol} is highest for lower pressure ratio, and it decreases as the pressure ratio increases. The effect of compressor speed is relatively less on η_{vol}, but it decreases slightly when the compressor is not working at the rated speed. The volumetric swept volume of the compressor is assumed to be 22cm^3.

2.1.4 Separator model with fractionation for SEC

The standard ejector cycle (SEC) has a separator in its layout resulting in the separation of the vapor-liquid phase. The fractionation inside the separator is modeled with the assumption that the separator is operating at a constant pressure and temperature. Figure 2(a) shows operation of the separator, whereas Figure 2(b) shows the Tw diagram for

R1234yf/R32 mixture for $P_{sep} = 1000\text{kPa}$. For a given mass fraction of R32 inside the separator ($w_{sep} = \frac{m_{sep,R32}}{m_{sep}}$), the separator temperature (T_{sep}) is a function of the vapor quality inside the separator (x_{sep}) for the given pressure (P_{sep}). Assuming an ideal separation, the quality at the vapor port of the separator is $x_{sepvo} = 1$ and the quality at the liquid port is $x_{seplo} = 0$. This allows to calculate the mass fraction of R32 at the vapor port (w_{sepvo}) and the liquid port (w_{seplo}) against T_{sep}. However, x_{sep} should be calculated based on the geometric and operational conditions of the separator. For solving fractionation inside the separator, the set of eleven equations and unknowns are given in Table 1. The Liquid level (LL) is assumed to be 0.5. The separator geometry is rectangular cuboid with an aspect ratio of 0.5 between the width and the height. The width and the depth are equal. The height of separator is assumed to be 12in.



(a) (b)

Figure 2 Fractionation modeling inside separator (a) Schematics of the separator (b) Tw diagram of R1234yf/R32

Table 1 Simulation table for calculating vapor and liquid composition in the separator due to fractionation

Equation	Known	Unknown	#E	#U
$T_{sep} = T(x_{sep}, P_{sep}, w_{sep})$	w_{sep}, P_{sep}	T_{sep}, x_{sep}	1	2
$w_{sepvo} = w(x_{sepvo}, P_{sep}, T_{sep})$	x_{sepvo}	w_{sepvo}	2	3
$w_{seplo} = w(x_{seplo}, P_{sep}, T_{sep})$	x_{seplo}	w_{seplo}	3	4
$V_{sep,v} = (1 - LL)V_{sep}$	LL, V_{sep}	$V_{sep,v}$	4	5
$V_{sep,l} = (LL)V_{sep}$		$V_{sep,l}$	5	6
$m_{sep,v} = \rho_v V_{sep,v}$		$m_{sep,v}, \rho_v$	6	8
$m_{sep,l} = \rho_l V_{sep,l}$		$m_{sep,l}, \rho_l$	7	10
$\rho_v = \rho(x_{sepvo}, P_{sep}, w_{sepvo})$			8	10
$\rho_l = \rho(x_{seplo}, P_{sep}, w_{seplo})$			9	10
$m_{sep} = m_{sep,v} + m_{sep,l}$		m_{sep}	10	11
$x_{sep} = \frac{m_{sep,v}}{m_{sep}}$			11	11

2.2 System modeling

Three system models are developed for this study by combining the component models introduced in the section 2.1. The models are developed in MATLAB using REFPROP (Lemmon et al., 2018) as the material library. It is assumed that there is no pressure drop inside any component. The cooling capacity of all the systems for matched capacity condition is fixed at 3kW. An enthalpy marching scheme is used for developing all the system models.

The first system model is for the baseline system working on the conventional vapor compression cycle having evaporator, compressor, condenser, and a throttling valve as an expansion device. The baseline system model has three variables P_{cpri}, P_{cpro} and compressor speed N. For studying the effects of fractionation, two ejector systems are considered. The first ejector system, working on the standard ejector cycle (SEC) as shown in Figure 3(a), offers fractionation as it has a separator. The high-side and low-side of the cycle has different refrigerant circulating compositions. The model has five variables, P_{cpri}, P_{cpro}, P_{eri}, x_{sep}, and N. The second ejector system, working on condenser outlet split (COS) cycle (Lawrence and Elbel, 2014), as shown in Figure 3(b), does not offer fractionation as it can have a receiver, instead of a separator. Thus, there can be only one circulating composition in the system set by the composition in the receiver, assuming there is no shift in composition due to differential holdup in the components like pipes and heat exchangers. The UA value of low and high temperature evaporator has been divided in a ratio of 75-25% of the evaporator UA value assigned in the SEC. The model has four variables P_{cpri}, P_{cpro}, P_{eri}, and N. The ejector mass entrainment ratio, ϕ_m is used as an input for the model.

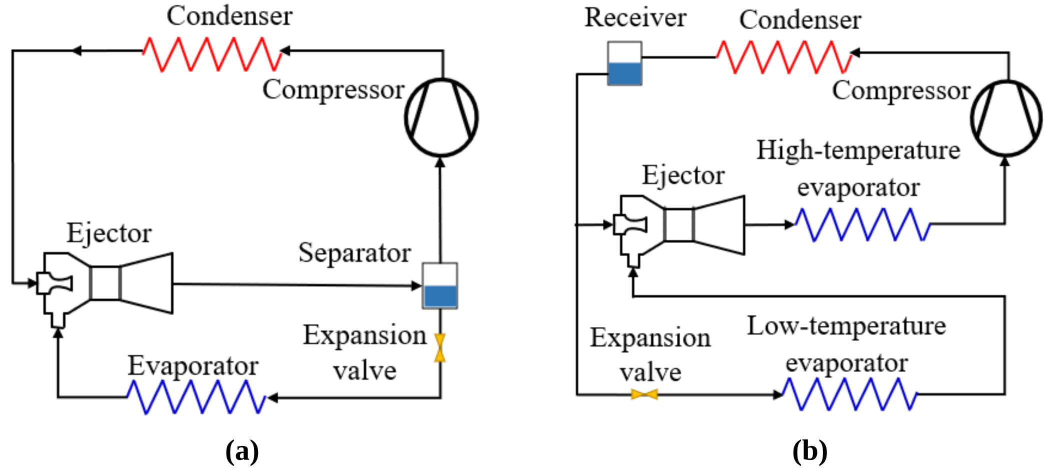


Figure 3 System layouts of (a) standard ejector cycle (SEC) (b) Condenser outlet split (COS)

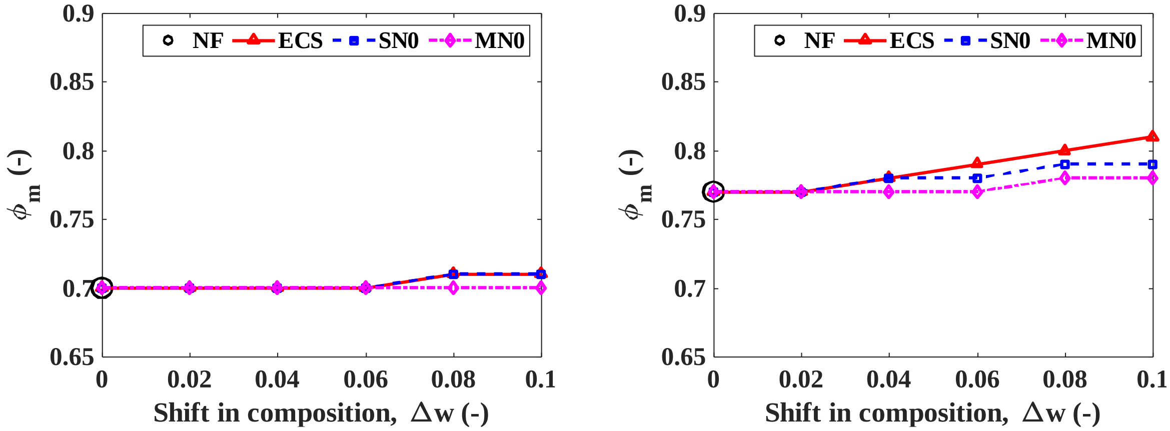
The system models are solved using lsqnonlin function available in the Optimization Toolbox of the MATLAB. The trust region-reflective algorithm (Coleman and Li, 1996) is used for finding solution of the model. For some conditions, the solver struggles with the convergence, but by changing the initial conditions for the model, the convergence can be achieved.

3. RESULTS AND DISCUSSION

3.1 Ejector performance with different compositions at the motive and the suction inlets

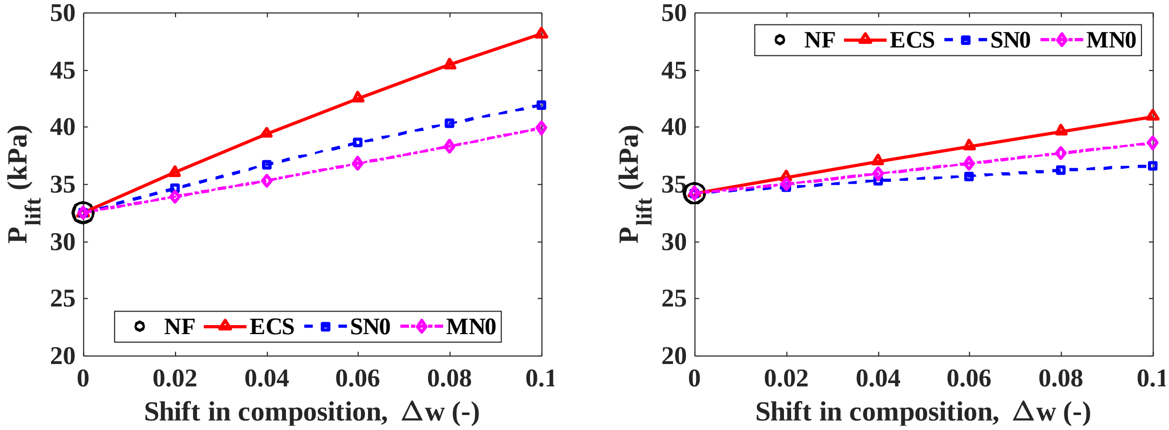
In this section, the effect of fractionation on the performance of an ejector as a component of the standard ejector cycle is presented. Two compositions of the R1234yf/R32 mixture are considered, namely R454B (R1234yf/R32 [0.689]) and R454C (R1234yf/R32 [0.215]). R454C has higher temperature glide than R454B. Different scenarios are considered for the analysis. In a no fractionation (NF) scenario, the ejector has same composition at the motive and the suction inlet. In the Equal Composition Shift (ECS) scenario, the composition at both the motive and the suction inlet changed equally in the range of $\Delta w_{mn} = \Delta w_{sn}$ = [0-0.1]. The mass concentration of R32 is increased at the motive nozzle (Δw_{mn}) while it is decreased for the composition at the suction inlet (Δw_{sn}). This change is in line with the physical system, as the suction inlet receives the liquid composition of the separator, while the motive inlet receives the vapor composition of the separator. Since, the vapor phase will have a higher concentration of volatile substance (R32 in this case) than liquid, therefore Δw_{mn} is increased whereas Δw_{sn} is decreased. The SN0 represents a scenario where there is no composition shift at the suction inlet, whereas only the motive inlet composition is changed by Δw_{mn}. Similarly, the MN0 represents a scenario where there is no composition shift at the motive inlet, while the suction inlet composition is changed by Δw_{sn}.

Figure 4-6 shows the result of change in composition for all the scenarios. The NF scenario is the left most data point against which other scenarios are compared. The composition with the higher temperature glide (R454C) appears to have negligible increase in the mass entrainment ratio as shown in Figure 4(a), whereas significant increase in the pressure lift is observed for all the scenarios as shown in Figure 5(a). The maximum pressure lift occurs when both the motive and the suction compositions are changed by the same amount. For R454B which has less temperature glide, both the mass entrainment ratio, shown in Figure 4(b) and the pressure lift, shown in Figure 5(b) increases. The ejector efficiency increased by almost 7% for ECS scenario for both the refrigerant mixtures as shown in Figure 6. However, the increase in the ejector efficiency for R454C is more sensitive to the change in the composition than it is for R454B.



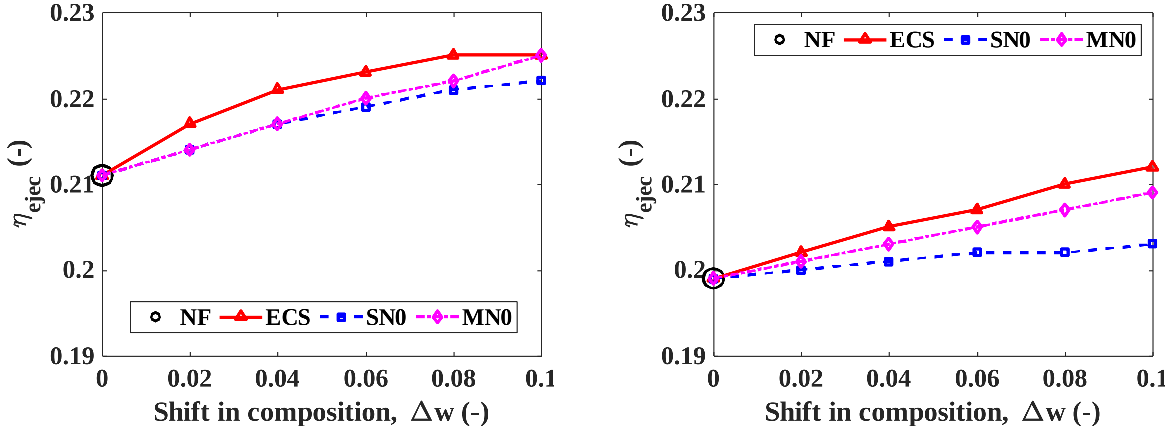
(a) R454C (b) R454B

Figure 4 Mass entrainment ratio as function of composition shift



(a) R454C (b) R454B

Figure 5 Pressure lift as function of composition shift



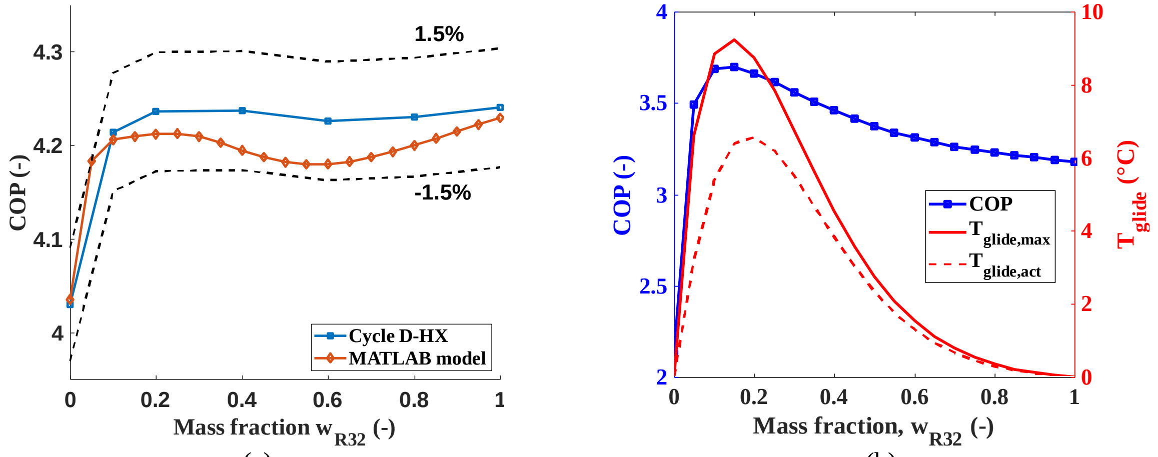
(a) R454C (b) R454B

Figure 6 Ejector efficiency as function of composition shift

The analysis shows that the fractionation appears to improve the ejector performance. It should be noted that in an actual system, the amount of composition difference at the motive and the suction inlets depends on the level of fractionation inside the separator.

3.2 Baseline system performance

The baseline (conventional) system model developed in MATLAB is compared with NIST's CYCLE_D-HX (Brignoli et al., 2017) which is developed for exploring potential of performance gain using different refrigerant mixtures. The component models of the two systems, and the model inputs are mentioned in section 2. Figure 7(a) shows the two models agree quite well not only in terms of numbers, but also in terms of trend. For R1234yf/R32 mixtures, the COP increases for small addition of R32 in R1234yf. However, the peak COP is not greater than the COP achieved with the pure R32 system. This can be because of the fixed compressor efficiency used in these models. Figure 7(b) shows the simulation result of MATLAB model with a variable speed compressor. The model predicts that the peak COP, higher than both pure R1234yf and R32 systems, will occur for the compositions with higher temperature glide. This trend is consistent with the reported trend in experimental studies (Mulroy et al., 1988).



(a) (b)

Figure 7 Simulation results (a) comparison of MATLAB model with CYCLE D-HX (b) MATLAB model with variable speed compressor

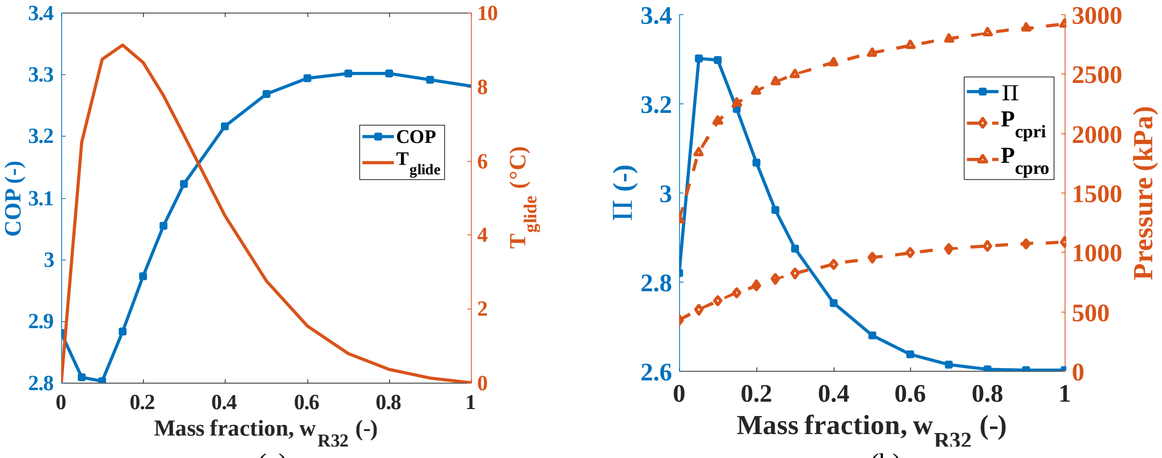
3.3 Ejector systems performance

3.3.1 SEC system performance with the zeotropic mixture

In section 3.1, it has been shown that fractionation improves the ejector performance. However, it is important that ejector performance improvement should also translate into an improvement in the system performance. Here the simulation results for SEC system are presented, and the effects of fractionation inside the separator are analyzed. Figure 8 shows simulation results for the SEC system in terms of a mass fraction sweep of R32 concentration for the matched capacity conditions. The mentioned mass fraction is the R32 mass fraction inside the separator, w_{sep}, whereas the model determines the mass fraction circulating in the high-side and the low-side by solving the fractionation inside separator at constant pressure and temperature. In Figure 8(a), the COP drops when small amount of R32 is added, and then it increases. The COP does not go significantly higher than the COP of the pure R32 system. This trend is different than what has been observed in Figure 7(b) for the baseline system. The drop in COP can be attributed to a sharp increase in the pressure ratio ($\Pi = P_{cpro}/P_{cpri}$). As the high-volatile substance (R32) is added to the R1234yf, both the low-side and the high-side pressures increases. However, the increase in the high-side pressure is quite sharp as R32 concentration is much higher in the high-side due to fractionation. The higher R32 concentration on the high-side means that the system will have higher high-side pressure for the same HTF conditions.

Figure 9 compares the performance of the SEC system with fractionation, and the baseline system. The result of the baseline system is same as shown in Figure 7(b). A hypothetical SEC system without fractionation is also added for the comparison. The high-side and the low-side have the same circulating compositions (fixed at separator) in this hypothetical SEC system. The results show that fractionation appears to drop the COP of the ejector system by -3%

for the highest temperature glide composition in comparison to the pure R1234yf system. When there is no fractionation, the system COP increases by 45%.



(a) (b)

Figure 8 Simulation results of SEC for different mass fractions of R32 in the separator (a) COP (b) Pressure ratio and compressor suction and discharge pressures

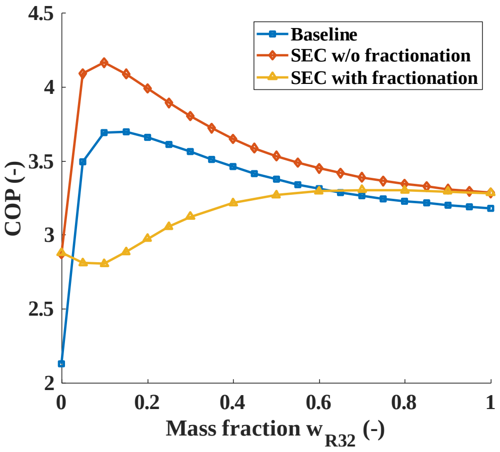
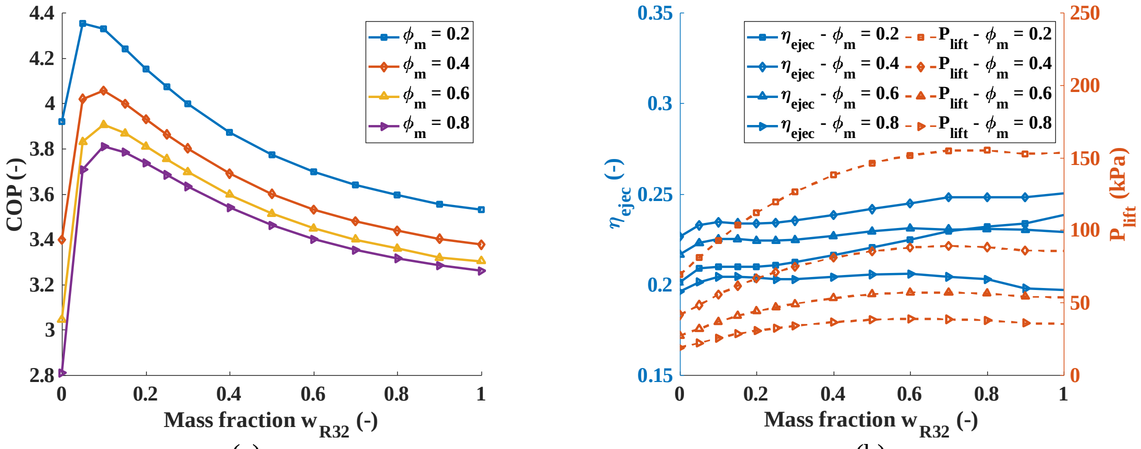


Figure 9 Comparison of SEC system performance with the baseline system, and the effects of fractionation

3.3.2 COS system performance with the zeotropic mixture

In the last section, the hypothetical SEC system without fractionation shows an increase in the COP. However, such a system is not physically realizable. The COS cycle offers an ejector system with a receiver/an accumulator, instead of a separator, and thus, the cycle can realize the same circulating composition throughout the system. Figure 10(a) shows the COS system's COP for different values of ejector's mass entrainment ratio. The COP peaks around the compositions with the highest temperature glide. The percentage gain in COP is highest, around 40% for $\phi_m = 0.8$, whereas the peak COP is predicted at 4.35 for $\phi_m = 0.2$ which is 10% higher than the COP of pure R1234yf system. Figure 10(b) shows that in the COS system, the pressure lift increases as the R32 concentration is increased. The increase is, however, more significant when the temperature glide is higher. The ejector efficiency, η_{ejec} seems to increase for lower ϕ_m, whereas it drops for $\phi_m = 0.8$ as R32 concentration is increased.



(a) (b)

Figure 10 COS system results (a) COP for different mass entrainment ratios (b) ejector performance

4. CONCLUSIONS

This paper studied the effects of fractionation on the performance of the ejector systems with the zeotropic mixture. The refrigerant mixtures of R1234yf/R32 are selected for the study because of their low-GWP. The study first developed component models for ejector, heat exchangers, compressor, and separator with fractionation. Later, two different ejector system models, and one baseline system were developed for understanding how fractionation can impact the performance of the ejector systems.

It is found that the ejector performance is increased due to the fractionation. The ejector efficiency can increase by up to 7% for an equal composition shift scenario. However, the study has noticed that the gain in the ejector performance due to fractionation is not translated into a gain in the system performance for matched capacity case in the SEC system. The COP decreased by -3% for the maximum temperature glide composition. The decrease in COP is largely due to sharp increase in the high-side pressure because of fractionation, thereby increasing the compressor work. A hypothetical simulation of no fractionation for SEC system shows an increase in COP by 45%. Similarly, the results from the COS system, which does not have fractionation due to receiver, shows an increase in COP by 10% for the entrainment ratio having the highest COP. These results point that achieving gain in the ejector system performance using the zeotropic mixture is tricky and probably depends on the cycle layout having receiver/accumulator or separator. The future experimental studies should consider different ejector cycle layouts to confirm the findings of this numerical study that fractionation is probably not suitable for the ejector systems with the zeotropic mixtures.

NOMENCLATURE

h	specific enthalpy	(kJ/kg)
LMTD	log-mean temperature difference	(ºC)
m	mass	(kg)
N	compressor speed	(min^{-1})
P	pressure	(kPa)
$\dot{Q}$	heat transfer rate	(kW)
s	specific entropy	(kJ/kgK)
T	temperature	(°C)
V	velocity	(m/s)
w	mass fraction of the volatile substance. i.e., R32	(-)
x	quality	(-)
η	efficiency	(-)
Π	pressure ratio	(-)
ρ	density	(kg/m^3)
ϕ_m	mass entrainment ratio	(-)

Subscript

d	diffuser of the ejector
mn	motive nozzle of the ejector
ms	mixing section of the ejector
sep	separator
sn	suction nozzle of the ejector

REFERENCES

Brignoli, R., Brown, J., Skye, H. & Domanski, P., 2017. Refrigerant performance evaluation including effects of transport properties and optimized heat exchangers, Int. J. Refrigeration. 80: 52-65.

Coleman, T. F., & Li, Y., 1996. “An Interior, Trust Region Approach for Nonlinear Minimization Subject to Bounds.” SIAM Journal on Optimization, Vol. 6, pp. 418–445.

Domanski, P. A., & McLinden, M. O., 1992. A simplified cycle simulation model for the performance rating of refrigerants and refrigerant mixtures. Int. J. Refrigeration. 15: 81-88.

Elbel, S., & Hrnjak, P., 2008, Experimental validation of a prototype ejector designed to reduce throttling losses encountered in transcritical R744 system operation, Int. J. Refrigeration, 31: 411-422.

Haider, M., & Elbel, S., 2020. Development of a new ejector performance map for design of an automotive air conditioning system. SAE World Congress, Detroit, MI, USA, April 21-23, Paper 2020-01-1244.

Kim, M., Kim, M. S., & Kim, Y., 2004. Experimental study on the performance of a heat pump system with refrigerant mixtures’ composition change. Energy. 10: 1053-1068.

Kornhauser, A. A., 1990. The use of an ejector as a refrigerant expander. International Refrigeration and Air Conditioning Conference.

Lawrence, N., & Elbel, S., 2014. Experimental investigation of a two-phase ejector cycle suitable for use with low-pressure refrigerants R134a and R1234yf. Int. J. Refrig. 38, 310–322.

Lawrence, N., & Elbel, S., 2016. Experimental investigation on the effect of evaporator design and application of work recovery on the performance of two-phase ejector liquid recirculation cycles with R410A. Appl. Therm. Eng. 100, 398–411.

Lemmon, E.W., Bell, I.H., Huber, M.L., & McLinden, M.O., 2018. NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 10.0, National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg.

MATLAB, 2021a. The MathWorks, Inc., Natick, Massachusetts, United States.

McLinden, M. O., & Radermacher, R., 1987, Methods for comparing the performance of pure and mixed refrigerants in the vapour compression cycle. Int. J. Refrigeration. 10: 318-325.

Mulroy, W., Kauffeld, M., McLinden, M., & Didion, D., 1988, Experimental Evaluation of Two Refrigerant Mixtures in a Breadboard Air Conditioner, DOE (U.S. Department of Energy)/ORNL (Oak Ridge National Laboratory) Heat Pump Conference, Washington, DC, US.

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