2021

Numerical Analysis For Performance Comparison Between Hybrid Ejector And Conventional Refrigeration Systems

Tokitaka Yoshida
University of Illinois at Urbana-Champaign, tokitaka@illinois.edu

Stefan Elbel
Creative Thermal Solutions, Inc.

Numerical Analysis for Performance Comparison Between Hybrid Ejector and Conventional Refrigeration Systems

Tokitaka YOSHIDA[(a,b)], Stefan ELBEL[(a,c,*)]

(a) University of Illinois at Urbana-Champaign, Department of Mechanical Science and Engineering, Air Conditioning and Refrigeration Center, 1206 West Green Street, Urbana, IL 61801, USA

(b) Fuji Electric Co., Ltd., 1 Fujimachi, Hino-city, Tokyo, 1918502, Japan

(c) Creative Thermal Solutions, Inc., 2209 North Willow Road, Urbana, IL 61802, USA

(*) Corresponding author: elbel@illinois.edu

ABSTRACT

Recently, the utilization of low-grade thermal energy has gained increased attention as an attractive opportunity to save energy. Heat driven ejector refrigeration systems are among a number of promising solutions for utilizing thermal energy from waste heat. However, the main drawbacks of this system are low efficiency at off-design conditions and difficult controllability. Hybrid ejector refrigeration system is a promising solution for overcoming these drawbacks. In this system, a booster compressor is installed in order to improve the efficiency for a wide range of conditions and substantially improve controllability. In this study, a numerical efficiency analysis for hybrid refrigeration ejector system is performed and compared with conventional ejector system and vapor compression system. The investigations are focused on chilled water supply conditions (evaporation temperature is 5 °C) at various ambient temperature conditions ranging from 15 °C to 35°C. The seasonal performances in Tokyo and Los Angeles for each system are compared. R1234ze(E), which is a promising low-GWP refrigerant, is used in the system. The calculation results show that the hybrid system performance is 142 % higher than ejector system, 16 % higher than vapor compression system in Tokyo, and 86 % higher than ejector system, 21 % higher than vapor compression system in Los Angeles at summer conditions. Therefore, this study clearly demonstrates the potential of the hybrid ejector system.

Keywords:
heat driven ejector refrigeration system, hybrid ejector refrigeration system, vapor compression heat pump system, efficiency analysis, ejector numerical model

1. INTRODUCTION

In recent years, the utilization of low-grade thermal energy has developed into an attractive opportunity to save energy. Heat driven ejector refrigeration systems are one of the promising solutions for utilizing thermal energy from waste heat, which is a free energy source in many fields (*e.g.* from industrial processes or solar heat). In this system, an ejector driven by thermal energy is used instead of a mechanical compressor. Therefore, it requires much lower electric energy than conventional vapor compression refrigeration systems. The main applications of this system are seen in cooling of industrial and commercial buildings, such as chilled water supply, air conditioning, and process cooling.

However, the main drawbacks of this system are low efficiency at off-design conditions and difficult controllability. Especially at high condensation temperature conditions such as in summer, the performance of the ejector drops dramatically, because the pressure lift (pressure difference between suction flow and discharge flow) is higher. Therefore, this system might not be able to work in summer. Although this system shows high performance at moderate conditions, those drawbacks present severe obstacles that currently prevent a widespread application of the technology.

Hybrid ejector refrigeration system is a promising solution for solving these drawbacks. In this system, a booster compressor is installed in order to improve the efficiency for a wide range of conditions and to substantially improve controllability. Because of its potential, hybrid ejector systems are receiving increased attention these days. Wang *et al.* (2016) performed an experimental system comparison with conventional vapor compression system for an air-conditioning application using R134a and found 34% higher performance. Chen *et al.* (2019) performed a numerical analysis and revealed a 40% higher performance for the hybrid ejector system. However, the number of studies is still very limited. In this study, a numerical efficiency analysis for hybrid ejector system for R1234ze(E) is performed and compared with a conventional, heat driven ejector system and a vapor compression system.

2. HYBRID EJECTOR REFRIGERATION SYSTEM

2.1 System configuration

The hybrid driven ejector refrigeration system described by Wang *et al.* (2016) is shown in Figure 1. A booster compressor is installed at the suction of the ejector. Three valves are installed around the ejector and compressor to change the flow path. Figure 2 (a)-(c) show the three possible operation modes for this system. One mode is vapor compression mode, which is conventional vapor compression system, and it will be used at high ambient temperature conditions. Another mode is ejector mode, which is a conventional, heat driven ejector system and it will be used at low ambient temperature conditions. The last mode is hybrid mode, which is combination of compression and ejector system. One of the biggest advantages of this system is that an appropriate mode will be chosen to maximize the performance for various conditions.

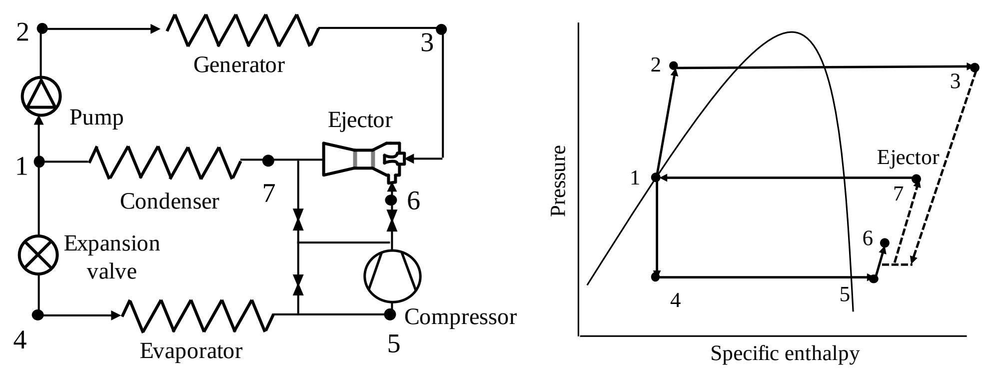
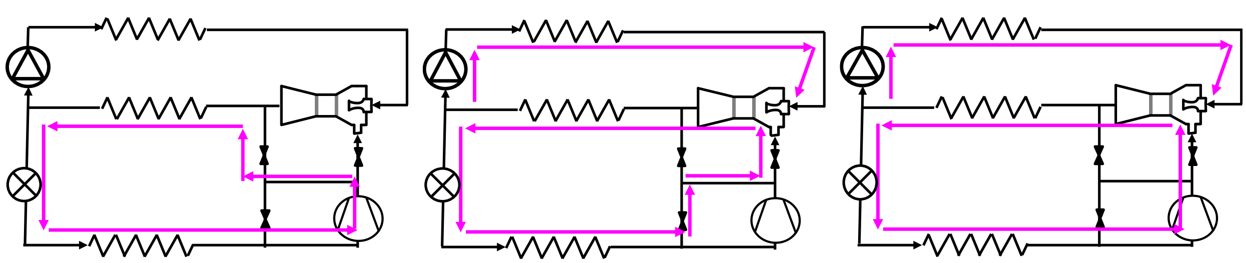


Figure 1: Hybrid ejector refrigeration system



(a) Compression mode (b) Ejector mode (c) Hybrid mode

Figure 2: Three operation modes for hybrid ejector refrigeration system

3. NUMERICAL ANALYSIS

3.1 Calculation model

In this study, a validated ejector model which is based on Huang *et al.* (1999) is used. This model is modified from ideal gas model to real gas model in order to calculate more accurate results. The detailed calculation procedure is described by Yoshida *et al.* (2021). In Yoshida *et al.'s* (2021) work, the condensation temperature T_c is an input value, and the mixing section area A_m is optimized at each condition. In this study, the condensation temperature T_c will be calculated by using a fixed mixing section area A_m, because the ejector geometry is not varied during operation.

Two COPs (Coefficient of Performance) are defined to evaluate each system. Electric COP (COP_e) is the ratio of cooling capacity and electric power input which is the well-known definition for vapor compression systems. Thermal COP (COP_{th}), which is defined for conventional, heat driven ejector systems and hybrid ejector systems, is the ratio of cooling capacity and input heat. COP definitions are shown in following Equations (1), (2).

$$COP_e = \frac{Q_c}{W_{pump} + W_{comp}} \tag{1}$$

$$COP_{th} = \frac{Q_e}{Q_g} \tag{2}$$

3.3 Calculation conditions

Table 1 shows the calculation conditions. The calculation assumes a chilled water supply condition (T_e=5 ℃) at various condensation temperatures T_c ranging from 20 ℃ to 40 ℃ (corresponding to ambient temperatures of 15 ℃ to 35 ℃). At the above conditions, generation pressure P_g for ejector system and hybrid system, and ejector suction pressure P_s (or compressor discharge pressure) for hybrid system can be controlled. In this calculation, pump and compressor control are assumed in order to find the appropriate generation pressure P_g and ejector suction pressure P_s for maximum performance. The detailed calculation procedure is shown in Figure 3. The generation pressure P_g, which will be controlled by the pump, is varied to achieve the required condensation pressure P_c. Ejector suction pressure P_s, which will be controlled by compressor, is adjusted to obtain maximum COP_e. R1234ze(E), a promising low-GWP refrigerant, is used in the system. A Newton-Raphson solver method implemented in VBA (Visual Basic for Applications) is integrated with RefProp for fluid property calculations.

Table 1: Calculation conditions

Evaporation temperature T_e	5 ℃
Condensation temperature T_c (Ambient temperature)	20-40 ℃ (15-35 ℃)
Primary flow superheat $T_{sh,g}$	5 K
Suction flow superheat $T_{sh,e}$	5 K
Subcooling of condenser outlet	2 K
Pump efficiency	0.2
Adiabatic efficiency of compressor	0.7
Volumetric efficiency of compressor	0.9
Throat area and mixing area ratio A_m/A_t	2.36
Generation pressure P_g	Controlled to achieve required P_c
Ejector suction pressure P_s	Controlled to obtain maximum COP_e

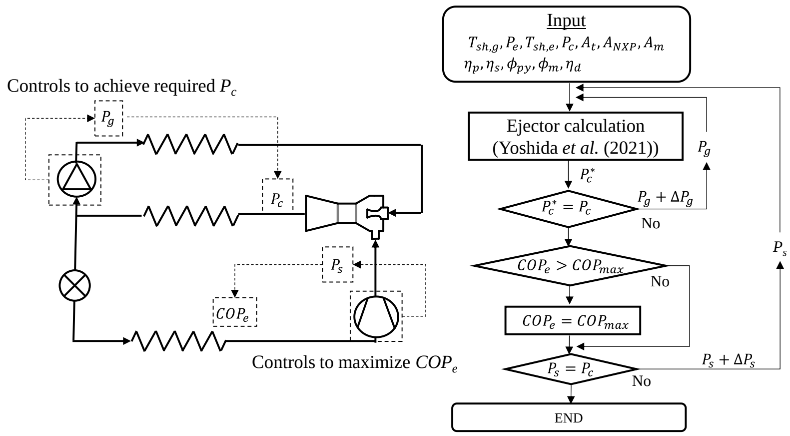


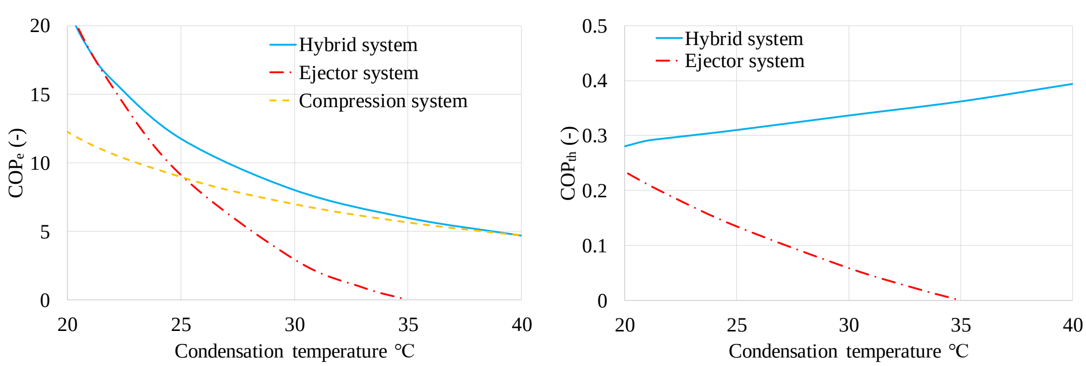
Figure 3: Calculation procedure for hybrid ejector system

4. RESULTS

4.1 COP comparison results

Figure 4 (a) shows the effect of condensation temperature on COP_e each of the systems. Conventional ejector system shows higher COP_e at lower condensation temperatures, but it cannot be operated at higher condensation temperatures. On the other hand, vapor compression system can perform across the entire range of at all ambient temperature conditions. However, the hybrid ejector system shows the highest COP_e at any of the conditions. Its performance is close to ejector system at low condensation temperatures and is close to compression system at high condensation temperatures. This is because optimal compressor work will be zero at low condensation temperature conditions where it will become a conventional ejector system. At high condensation temperatures, its performance will be similar to vapor compression system because the ejector does not perform well as it would have to deliver a very large pressure lift between the evaporation pressure and the much-elevated condensation pressure. Based on these results, the hybrid ejector system is expected to always perform at least as well as the higher performing system at any given condition. This is because the hybrid ejector system will switch modes if the conventional system shows higher performance. Regarding COP_{th}, the hybrid ejector system shows higher performance than the conventional ejector system (Figure 4 (b)). It means that it requires less thermal energy (*e.g.* waste heat of industrial processes or from solar heat collectors) than conventional ejector system. COP_{th} for vapor compression system is not defined, because thermal energy is not required as an input. One of the advantages of the hybrid system is that thermal energy is not always required for operation. If the thermal energy input is not sufficient to operate the system, it will switch to the vapor compression mode. This point makes the system robust and plays an important role for practical applications.

Figure *5* shows the required waste heat conditions ((a) temperature, (b) capacity) at each condition. These results show that the hybrid ejector system requires lower waste heat temperature and capacity than the conventional ejector system. Therefore, the hybrid ejector system can be applied at wide range of waste heat temperature and capacity conditions.



(a) (b)

Figure 4: Effect of condensation temperature on (a) electric COP and (b) thermal COP

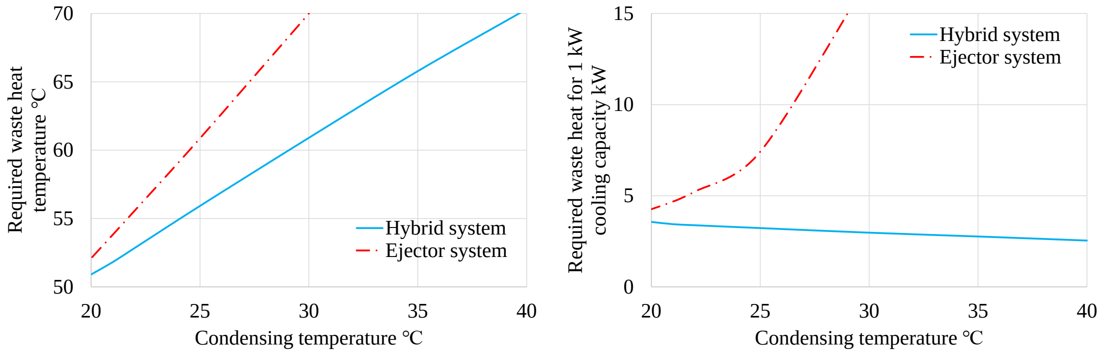


Figure 5: Required waste heat conditions (a) temperature, (b) capacity

4.2 Seasonal COP comparison results

In order to compare the seasonal performance, seasonal electric COP (COP_e) is calculated based on the results discussed in the previous section. Figure 6 shows the seasonal COP comparison based on average temperatures in Tokyo and Los Angeles in 2019. Ejector system shows quite high theoretical COP_e in winter in Tokyo, but it might not work in summer. In Los Angeles, its performance is more stable than in Tokyo, because the seasonal temperature changes are smaller than in Tokyo. As described in the previous section, the hybrid system always shows the highest performance for any of the ambient temperature conditions by means of utilizing the advantages of both ejector and vapor compression systems.

Figure 7 shows the annual average COP_e for Tokyo and Los Angeles. In this calculation, operating time is assumed to be constant for each month. The results show that the hybrid system's annual performance is 6.5 % higher than that of the ejector system, 122 % higher than vapor compression system in Tokyo, and 15 % higher than ejector system, 51 % higher than vapor compression system in Los Angeles. However, it is obvious that the chilled water demand is higher in summer than in winter. Therefore, summer average COP_e (from June to September) is also compared in Figure 7. At summer conditions, the hybrid system performance is 142 % higher than the ejector system, 16 % higher than vapor compression system in Tokyo, and 86 % higher than the ejector system, 21 % higher than vapor compression system in Los Angeles. These results reveal that hybrid ejector system shows much higher annual performance than conventional systems.

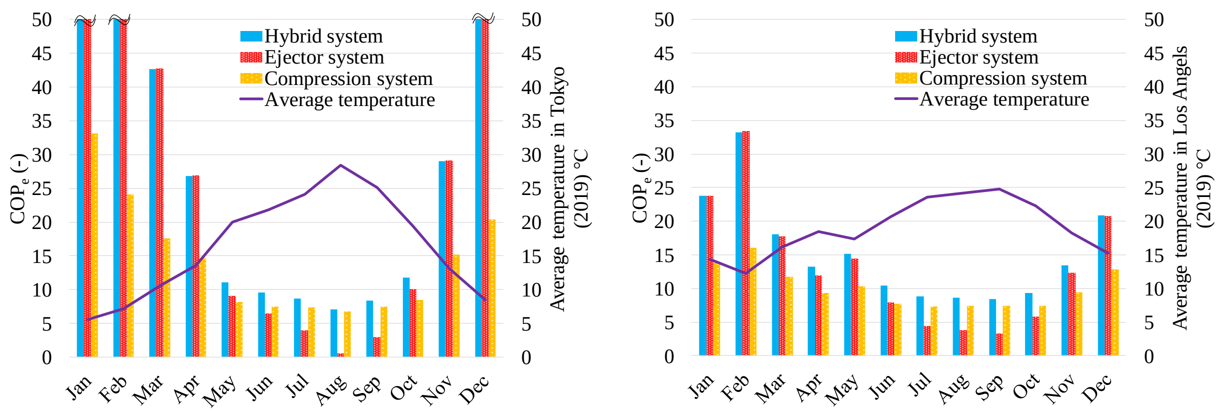


Figure 6: Seasonal COP comparison result based on average temperature in Tokyo and Los Angeles in 2019

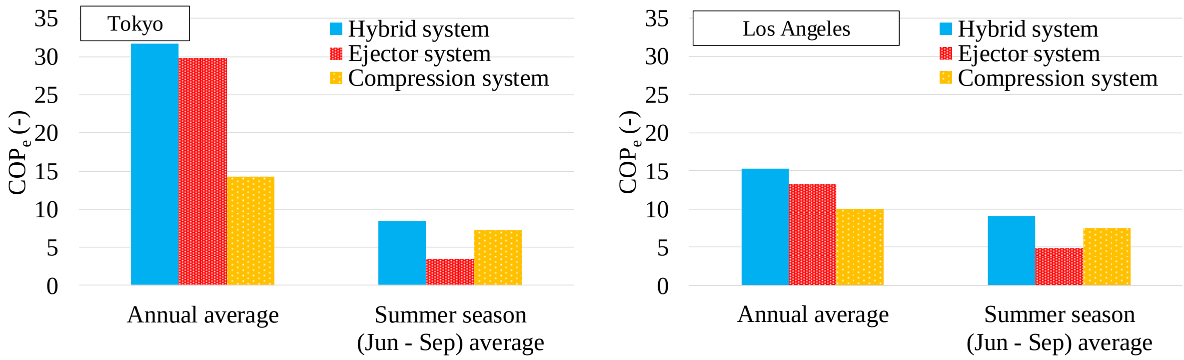


Figure 7: Annual average COP and summer average COP for Tokyo and Los Angeles in 2019

5. CONCLUSIONS

In this study, a numerical efficiency analysis for hybrid ejector system, conventional ejector system, and vapor compression system is performed for various temperature conditions. Seasonal performances are compared for each system. The results reveal the following and demonstrate the large potential to save energy with hybrid ejector systems.

- Conventional ejector system shows high performance at low ambient temperature conditions, but the performance drops dramatically at high ambient temperature conditions.
- Vapor compression system can be operated at all ambient temperature conditions.
- Hybrid ejector system shows the highest performance at all ambient temperature conditions by means of utilizing advantages of both the ejector and the vapor compression system.
- Hybrid ejector system shows much higher seasonal performance than conventional ejector and vapor compression systems.
- Robustness and controllability of the hybrid system are higher than for the conventional, heat driven ejector system.

NOMENCLATURE

A	Area	mm^2
COP_e	Electric coefficient of performance	-
COP_{th}	Thermal coefficient of performance	-
P	Pressure	Pa
Q	Heat	kW
W	Mechanical work	kW
η	Efficiency	-
ϕ	Coefficient of efficiency	-

Subscript

c	Condenser
$comp$	Compressor
e	Evaporator
d	Diffuser
g	Generator
m	Mixing
NXP	Nozzle exit point
p	Primary flow
$pump$	Pump
s	Suction flow
sh	Superheat

REFERENCES

1) Chen, W., Li, X., Shang, S., Shi, W., Cao, Y., & Wang, B. (2019), Simulation of the performance of a gas-fired hot water system with compression-enhanced ejector heat pump using R152a, *Applied Thermal Engineering 162*, 114-159.
2) Huang, B.J., Chang, J.M., Wang, C.P., & Petrenko, V.A. (1999), A 1-D analysis of ejector performance, *International Journal of Refrigeration 22*, 354-364.
3) Japan Meteorological Agency, http://www.jma.go.jp/jma/indexe.html
4) Los Angeles Almanac, (2020, December), High/Low & Average Temperatures By Month & Year Downtown Los Angeles, http://www.laalmanac.com/weather/we04a.php
5) Yoshida, T., Matsubara, T., Ajima, M., Iwasaki, M., & Elbel, S. (2021), Numerical Analysis for Heat Driven Ejector Refrigeration Systems for Various Refrigerants, *Proceedings of 18th International Refrigeration and Air Conditioning Conference 2233, Purdue,* the US.
6) Wang, H., Cai, H., Wang, Y., Yan, J., & Wang, L. (2016), Experimental study of the behavior of a hybrid ejector-based air-conditioning system with R134a, *Energy Conversion and Management 112*, 31-40.