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ABSTRACT

In this study, a numerical efficiency analysis for ejector refrigeration systems driven by low grade waste heat (65-85 °C) is performed. A 1-D numerical ejector model which was validated is applied to estimate the characteristics of the ejector. Investigation is focused on various refrigerants such as HFC (R134a, R245fa, R365mfc), HFO (R1234yf, R1234ze(E), R1233zd(E), R1336mzz(Z)), and natural refrigerants (NH_3, R600, R600a), and their COPs (Coefficient of Performance) are compared. Main operating conditions (*e.g.* generation temperature, evaporation temperature, condensation temperature) are also considered to compare the system characteristics for each refrigerant. Simulations are performed for different operating conditions and their effects on system performance is analyzed. The results show that high NBP (Normal Boiling Point) refrigerants tend to show higher theoretical performance because of their high latent heat. In addition, it is found that sensitivity of generation temperature is less than evaporation temperature and condensation temperature.

Keywords:
heat driven ejector refrigeration system, refrigerant comparison, HFO refrigerant, natural refrigerant, efficiency analysis

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.

Regarding system performance, refrigerant selection is a critical issue not only for performance but also in system design, safety, and environmental impact. Sun (1999) compared eleven refrigerants (water, R11, R12, R113, R21, R123, R142b, R134a, R152a, RC318, R500) theoretically and concluded that R152a shows the highest performance and water shows the lowest performance. In Sun's (1999) work, CFCs (chlorofluorocarbons, *e.g.* R11, R12, R113) and HCFCs (hydrochlorofluorocarbons, *e.g.* R123, R142b) are considered as candidates, but those refrigerants are nowadays restricted because of ODP (Ozone Depletion Potential).

Instead of CFCs and HCFCs, HFCs (hydrofluorocarbons) have been widely used in refrigeration field. Gil *et al*. (2015) compared performance of HFCs and HCs (hydrocarbons) and concluded that R236fa showed the highest performance. However, HFC refrigerants (*e.g.* R134a, R152a) which have high GWP (Global Warming Potential) are also considered as a critical issue and might be restricted in the near future. In order to replace currently used refrigerants, various new refrigerant options such as HFO (hydrofluoroolefin) and natural refrigerants are being considered for use in refrigeration systems.

Based on the background, system performance comparison for HFO refrigerants is required since most researches have been focusing on the HFCs so far. In this study, numerical efficiency analysis for ejector refrigeration systems driven by low grade waste heat is performed. Investigation is focused on various refrigerants such as HFC (R134a, R245fa, R365mfc), HFO (R1234yf, R1234ze(E), R1233zd(E), R1336mzz(Z)), and natural refrigerants (NH_3, R600, R600a), and their COPs (Coefficient of Performance) are compared.

2. HEAT DRIVEN EJECTOR REFRIGERATION SYSTEM

2.1 System configuration

A heat driven ejector refrigeration system is shown in Figure 1. The system is based on the so-called thermo-compressor cycle, which is a combination of a liquid pump, a heat driven ejector, an expansion valve, and three heat exchangers (a generator, a condenser, an evaporator). A heat driven ejector is introduced instead of mechanical compressor. The expansion valve, the condenser and the evaporator perform in the same way as the vapor compression system. The generator is introduced to absorb the available low-temperature waste heat. The pump and the generator produce high pressure and high temperature gas flow that is the motive flow of ejector.

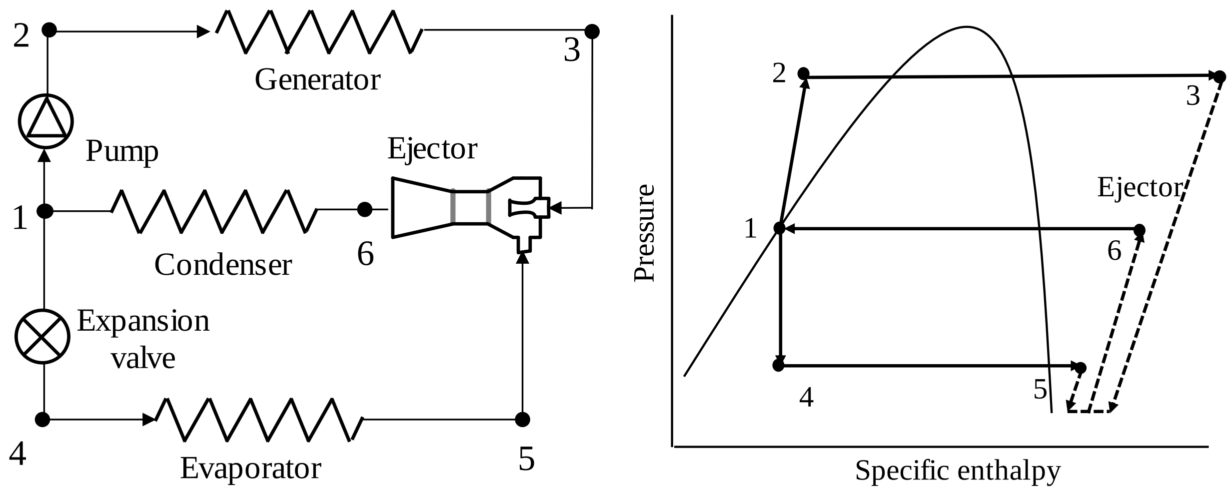

Figure 1: Heat driven ejector refrigeration system

2.2 Refrigerant selection

There are several aspects to consider when choosing an appropriate refrigerant.

- High theoretical value of COP.
- Appropriate thermodynamic properties (*e.g.* latent heat, pressure, density, viscosity).
- Less impact on the environment (ODP is 0, GWP is low).
- Safety (non-flammable, non-toxic).
- Low cost.

Unfortunately, the perfect refrigerant does not exist because some characteristics are trade-offs. For example, a low GWP refrigerant is often flammable, or a high-latent-heat refrigerant might be a low-density refrigerant. Therefore, refrigerant selection will be conducted with priorities and compromises.

Table 1 shows that the refrigerant candidates for heat driven ejector system. HFCs have been widely used instead of high ODP refrigerants (CFCs, HCFCs). HFCs' advantage is chemically stable: non-flammable and non-toxic. However, because of their stability, their GWP is high. Natural refrigerants are expected as alternatives of HFCs because their GWPs are relatively low. Nevertheless, natural refrigerants also have disadvantages. For instance, NH_3 is a toxic refrigerant, and organic solvents (*e.g.* R600, R600a) are highly flammable refrigerants. Under such a background, HFOs are promising refrigerants for heat driven ejector system. Their GWPs are relatively lower than HFCs' and their chemical stability (flammability and toxicity) is better than natural-refrigerant candidates.

Table 1: Refrigerant candidates for heat driven ejector system

		Critical temperature °C	**Critical pressure kPa**	**ODP**	**GWP**	**Flammability**	**Toxicity**	**Safety class**
HFC	R134a	101.1	4059	0	1430	NO	NO	A1
	R245fa	154.0	3651	0	1050	NO	NO	A1
	R365mfc	186.9	3266	0	794	N/D	N/D	N/D
HFO	R1234yf	94.7	3382	0	4	YES (low)	NO	A2L
	R1234ze(E)	109.4	3635	0	6	YES (low)	NO	A2L
	R1233zd(E)	165.9	3624	0	1	NO	NO	A1
	R1336mzz(Z)	171.3	2903	0	2	NO	NO	A1
Natural	NH_3	132.3	11333	0	0	YES (low)	YES	B2L
	R600	151.9	3796	0	4	YES (high)	NO	A3
	R600a	134.7	3629	0	3	YES (high)	NO	A3

3. NUMERICAL ANALYSIS

3.1 Ejector model

In order to analyze the system performance, the ejector model would be the key factor. A number of researchers have been working on the ejector modeling such as 1D modeling or 2D, 3D modeling (CFD). He *et al*., (2009) summarized the progress of ejector modeling and showed several mathematical models by previous authors. In those models, Huang *et al*.'s (1999) model has been widely used and cited in lots of previous works. Figure 2 shows the principle schematic of heat driven ejector proposed by Huang *et al*. However, one drawback of Huang's model is that it assumes ideal gas. Figure 3 shows the compressibility factor which describes the deviation of real gas behavior from ideal gas. It is defined by Equation (1), and where for *Z*=1, the ideal gas assumption is valid.

$$Z = \frac{P}{\rho RT} \tag{1}$$

According to this result, ideal gas assumption may cause 10-40 % difference when calculating refrigerant density. Therefore, the authors modified Huang's model with real gas assumption. The assumptions are following,

- The flow inside the ejector is steady and one dimensional.
- The kinetic energy at the inlets of primary and suction ports and the exit of diffuser are negligible.
- Component efficiencies (η_p, η_s, η_d, ϕ_m, ϕ_{py}) are proposed for simplicity in form of isentropic relations (their values will be discussed later).

- Mixing occurs at hypothetical throat (or section y-y) which is inside the constant-area mixing section.
- Suction flow is choked at hypothetical throat (so-called double choking condition).
- The ejector is adiabatic.
- Fluid property is calculated by RefProp database.

The calculation procedure is shown in Figure 4. In this calculation, throat pressure P_t, nozzle exit position pressure P_{NXP}, mixing pressure P_m, diffuser inlet density $\rho_{d,in}$ and mixing area A_m are solved implicitly.

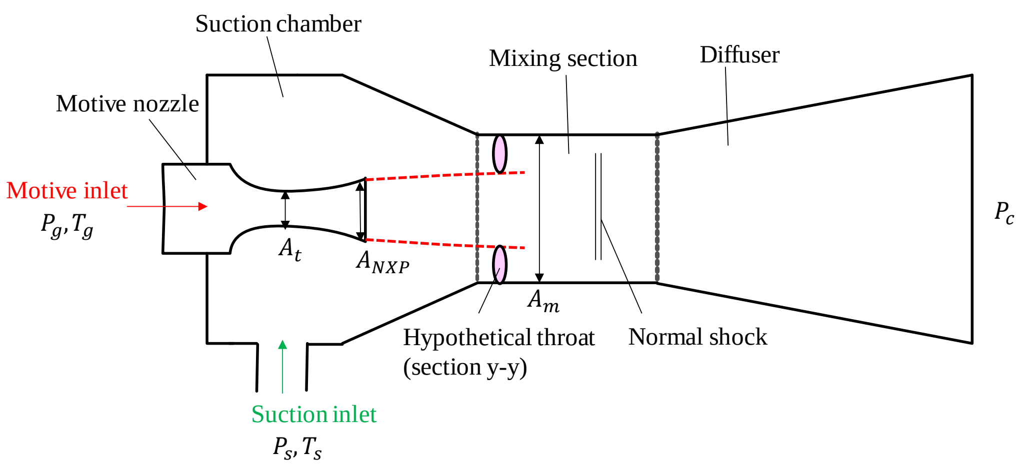

Figure 2: Principle schematic of heat driven ejector

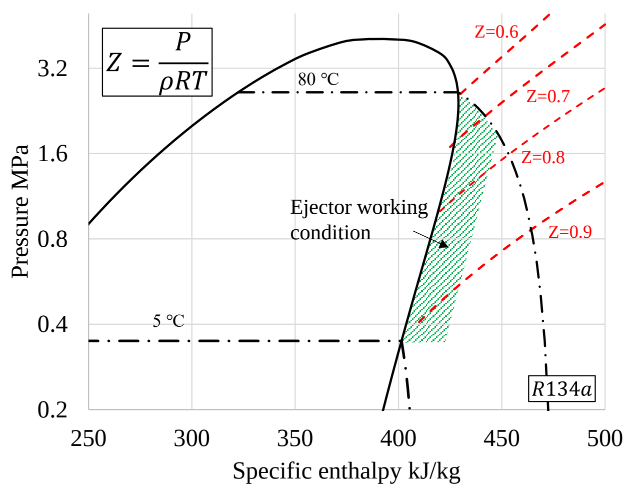

Figure 3: Typical values of compressibility factor in region of interest

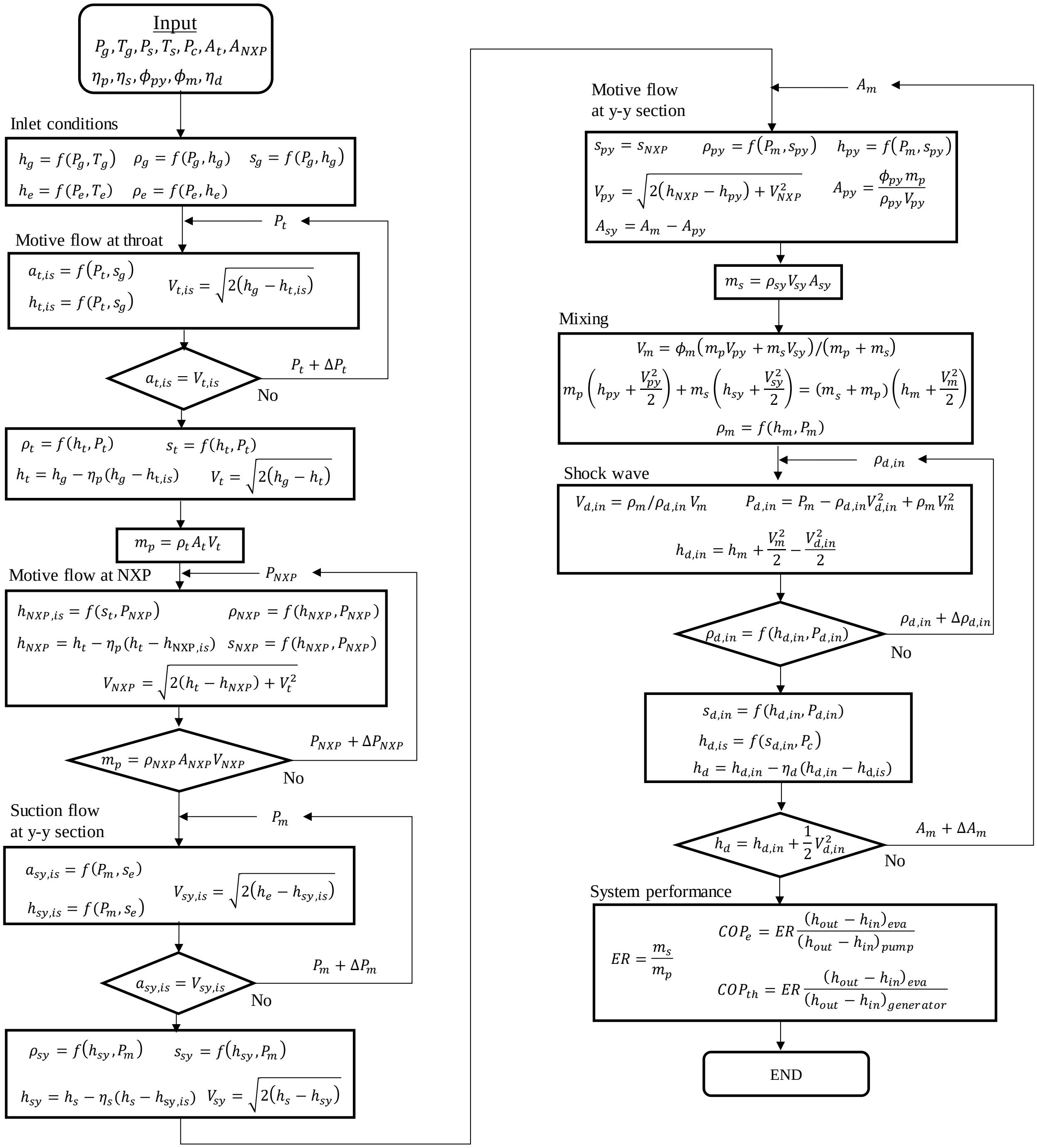

Figure 4: Ejector model calculation procedure

3.2 Model validation

In order to assess the accuracy of the model, both ideal gas model (proposed by Huang *et al.* (1999)) and real gas model (proposed in this work) are compared with experimental data. Equations (2)-(4) show the definitions of each component efficiency based on Huang *et al.* (1999).

$$\eta_p = \frac{}{_{,is}} = \frac{}{_{,is}} \tag{2}$$

$$\phi_{py} = \frac{\rho_{py} \quad _{py} \quad _{py}}{_{p}} \tag{3}$$

$$\eta_s = \frac{_{s} \quad _{sy}}{_{s} \quad _{sy,is}} \tag{4}$$

$$\phi_m = \frac{(\quad _{p} \quad _{s} \quad _{m}}{_{p} \quad _{py} \quad _{s} \quad _{sy}} \tag{5}$$

$$\eta_d = \frac{_{d,in} \quad _{d}}{_{d,in} \quad _{d,is}} \tag{6}$$

Table 2 shows the range of component efficiencies in previous works and their average values. Component efficiencies are critical to the ejector performance and appropriate values should be chosen. In this calculation, average values from previous works (Chen *et al.* (2017), Liu *et al.* (2017), Chen *et al.* (2014), Cardemil *et al.* (2012)) are used. Figure 5 shows the validation result of ideal gas model and real gas model. Experimental data is provided by Huang *et al.* (1999). Entrainment ratio (= suction mass flow rate / motive mass flow rate), which is one of the most important values to evaluate the performance of an ejector, is compared. The result shows that the real gas model achieves higher accuracy (-9 to +17 %) than Huang *et al.* (1999)'s ideal gas model (-23 to +22 %). These differences are caused by refrigerant property accuracy, which has been discussed in previous section.

Table 2: Range of ejector component efficiencies

	Value range in previous works (Chen *et al.* (2017), Liu *et al.* (2017), Chen *et al.* (2014), Cardemil *et al.* (2012))	**Average value**
Nozzle efficiency η_p	0.90-0.98	0.94
Coefficient of the primary flow leaving the nozzle ϕ_{py}	0.76-0.80	0.78
Suction efficiency η_s	0.85-1.0	0.925
Mixing efficiency ϕ_m	0.88-0.96	0.92
Diffuser efficiency η_d	0.79-0.95	0.87

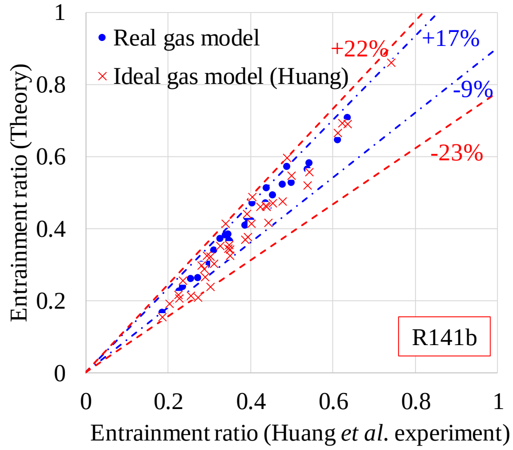

Figure 5: Validation results of real gas ejector model

3.3 Calculation conditions

Table 3 shows the calculation conditions. The rated condition assumes a chilled water supply condition (T_e=7 °C) in summer (T_c=30 °C). In addition, different generation, evaporation, and condensation temperature conditions are also used for additional calculations to evaluate the off-design performance.

Table 3: Calculation conditions

	calculation condition
Generation temperature T	65, <u>85</u> °C
Evaporation temperature T	3, <u>7</u> °C
Condensation temperature T	<u>30</u>, 35 °C
Primary flow superheat $T_{p,sh}$	<u>5 K</u>
Suction flow superheat $T_{s,sh}$	<u>5 K</u>
Condenser subcooling $T_{c,sc}$	<u>2 K</u>
Pump efficiency $\eta_{p\ \ mp}$	<u>0.2</u>

*<u>underline</u>: rated condition

4. RESULTS

Figure 6 (a) shows the comparison of results for the various refrigerants at the rated condition. The y-axis shows electric COP (COP_e) which is the ratio of cooling capacity and mechanical work. The x-axis shows thermal COP (COP_{th}) which is the ratio of cooling capacity and input heat. In this system, electric COP (COP_e) tends to be higher than that of the vapor compression system, because pump electric consumption is lower than for a compressor. Therefore, this system might be a promising solution for saving energy.

COP_e and COP_{th} tend to show a trade-off relationship. But typically, R365mfc, R1336mzz(Z), R1233zd(E), R600, NH_3 show high performance because they are located at high COP_e and high COP_{th} positions (upper right corner). However, refrigerant is not selected just by performance but also by other constraints such as cost, safety, viscosity, and so on. Figure 7 shows that the relationship between electric COP_e and NBP (Normal Boiling Point). Based on this result, high NBP refrigerants tend to show higher theoretical COP_e because their latent heat is higher. However, it might be difficult to handle them because their pressures are subatmospheric at the standard condition, the size of ejector might be bigger, and effect of pressure drop might not be negligible. NH_3 shows different characteristics but it is because its properties are quite different from others because of strong chemical bond (hydrogen bond).

Figure 6 (b)–(d) shows the effect of generation, evaporation, and condensation temperature on COP. According to the results, in case the generation temperature decreases, evaporation temperature decreases, or condensation temperature increases, both COP_e and COP_{th} decrease dramatically. However, although the working condition is different, their performance trends are similar. In addition, effect of generation temperature on COP_e is relatively small compared to evaporation temperature and condensation temperature effect. This is because the pump power consumption also decreases with lower generation temperature conditions.

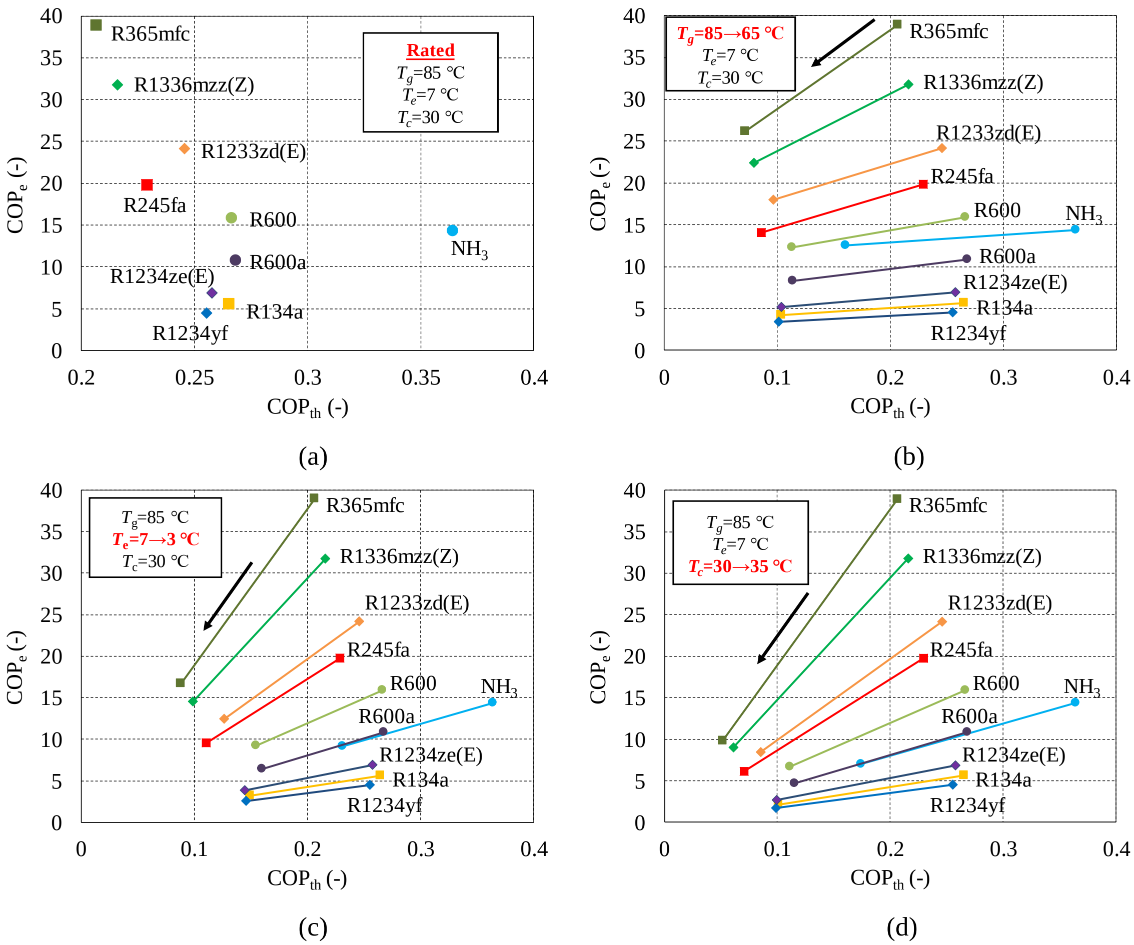

Figure 6: Simulation results for various refrigerants: (a) Rated condition, (b) Effect of generation temperature, (c) Effect of evaporation temperature, (d) Effect of condensation temperature

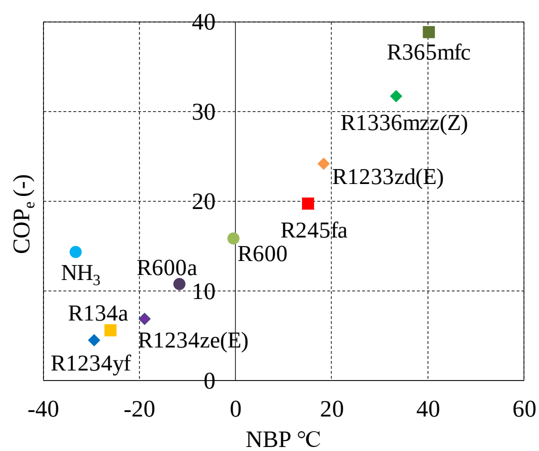

Figure 7: Relationship between electric COP and NBP

5. CONCLUSIONS

A numerical simulation for a heat driven ejector system is performed in order to compare relevant refrigerants such as HFC, HFO, and natural refrigerants. A new real gas 1D ejector model is proposed, and it achieved higher accuracy than previous models based on ideal gas assumption. Based on the results, the following conclusions have been reached.

- High NBP refrigerants tend to show higher theoretical COP_e because of their high latent heat.
- COP_e and COP_{th} change dramatically with the different conditions, but their performance trends are similar.
- Effect of generation temperature on COP_e is relatively less compared with the effects caused by evaporation temperature and condensation temperature changes.

The results of this work will contribute to selecting appropriate refrigerants for heat driven ejector refrigeration applications.

NOMENCLATURE

a	Speed of sound	m/s
A	Area	mm^2
P	Electric coefficient of performance	-
P	Thermal coefficient of performance	-
ER	Entrainment ratio	-
h	Specific enthalpy	J/kg
m	Mass flow rate	kg/s
P	Pressure	Pa
s	Specific entropy	J/kg/K
V	Velocity	m/s
ρ	Density	kg/m^3
η	Efficiency	-
ϕ	Coefficient of efficiency	-

Subscript

c	Condenser
e	Evaporator
d	Diffuser
g	Generator
is	Isentropic process
in	Inlet
m	Mixing
NXP	Nozzle exit point
p	Primary flow
py	Primary flow at y-y section
s	Suction flow
sc	Subcooling
sh	Superheat
sy	Suction flow at y-y section
t	Throat

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