

AN EJECTOR REFRIGERATION CYCLE FOR UTILIZING SOLAR THERMAL ENERGY

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ABSTRACT

Getting hot thermal energy from solar energy is popular but cooling with solar thermal energy is not spread so far. It is possible to reduce electricity demand to use solar energy for cooling in summer. We are designing a system of an ejector refrigeration cycle, especially concerning the configuration of ejector itself, which can generate cooling effect with high efficiency from academic viewpoint. The analytical [1], numerical [4], and experimental approaches are applied for designing the configuration. In this paper, the experimental viewpoint will be discussed.

Two different configuration ejectors were experimentally tested regarding the performance with an indoor testing device under the conditions of generating, condensing, and evaporating temperature ranges being about 58-69 °C, 17-35 °C, and 10-15 °C, respectively.

The performance reaches higher than 80 % at a certain combination of temperatures, although the performance of the ejectors strongly depends on the temperature combinations.

1. INTRODUCTION

Heavy consumptions of fossil energy are serious problem because large amount of carbon-dioxide is emitted and causes environmental destruction. Utilization of solar thermal energy is simple but seriously important from a viewpoint of restraining heavy consumption fossil energy

resources. In Japan, furthermore, the nuclear accidents in Fukushima have had an influence on denuclearization and enthusiastic promotion for renewable energy utilization.

In addition, a demand of cooling is increasing especially in city area because of the heat-island phenomenon, as well as in south-eastern Asia like Indonesia, Philippines, and Vietnam etc. because of their achieving economic development. As a result, the electric consumption all over the world is growing.

In order to utilize more renewable energy and adapt to widespread prevalence of cooling, an air-conditioning system powered by renewable energy is requested to be developed.

In this study, an ejector refrigeration cycle is introduced for solar air-conditioning system which utilizes solar thermal energy. Figure 1 shows a simple schematic diagram of an ejector refrigeration cycle. This cycle consists of an ejector and a condenser, an evaporator, a vapor generator (generator) and a pump.

The principle of ejector was known long time ago. Before 1900, it was used to get vacuum, and an ejector refrigeration cycle was known as early as 1901 with the development of a steam jet refrigerator by Le Blanc and Parson (Sokolov and Hershgal. 1989). The cycle has been studied for a long time by many researchers all over the world.

After thermal energy is provided to liquid-state working fluid in a vapor generator, the working fluid changes from

liquid state to gaseous state, and then the pressure of the working fluid increases. This high pressure and temperature working fluid is an energy source of the cycle.

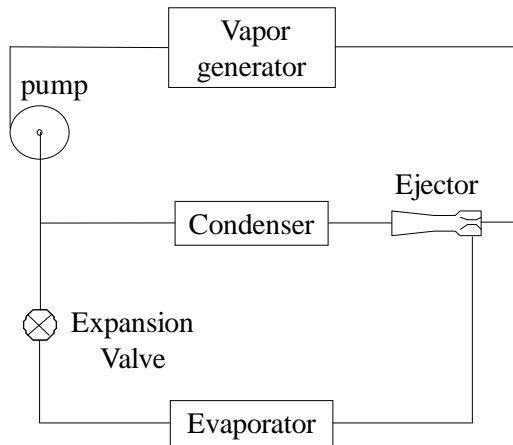


Fig. 1: A schematic of an ejector refrigeration cycle.

Figure 2 shows a schematic structure of an ejector. The high-pressure gaseous working fluid is sent to ejector and pass through the nozzle section. While passing, the gas is accelerated and expands with decreasing pressure. The supersonic primary flow becomes supersonic. As the pressure of the primary flow is lower than the pressure in evaporator, the working fluid in evaporator flows as the secondary flow at supersonic speeds.

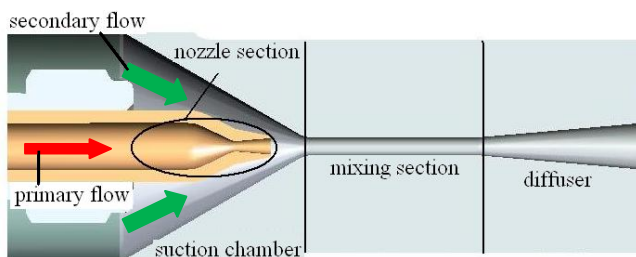


Fig. 2: Schematic structure of an ejector

In the suction chamber of ejector, the primary and secondary flows begin mixing and in the mixing section the two flows are mixed completely. In the diffuser, this mixed flow raises its own pressure with a transverse shockwave, and enter into condenser.

In condenser, the working fluid changes from gaseous state to liquid state. The liquid is sent to generator by pump. Power consumption by pump is small, which can be provided by photovoltaic cells. Some of the liquid is sent to evaporator through expansion valve.

In evaporator, the liquid working fluid evaporates at lower pressure and absorbs heat from the ambient.

Advantage of this cycle is that the cycle is activated by heat input, even if low-grade thermal energy at about 60 °C. Therefore heat resources such as solar thermal energy, geothermal energy and exhaust heat from factories etc. can be effectively utilized. And, ejector itself is simple, so this cycle would require only light maintenance.

Figure 3 shows a schematic diagram of an example of an ejector air-conditioning system utilizing solar energy.

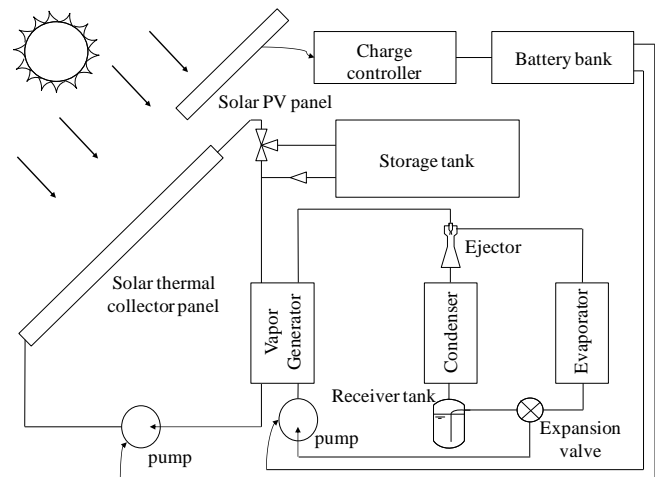


Fig. 3: An ejector air-conditioning system utilizing solar Energy.

This system consists of solar thermal collector panels, an ejector cycle for cooling, and PV panel to generate electricity for moving two pumps. By storing solar thermal energy in a storage tank, cooling air-conditioning can be operated even in night time.

2. EXPERIMENT

2.1 Experimental setup

In order to apply an ejector refrigeration cycle to the air-conditioning system, it is necessary to figure out the characteristics of an ejector refrigeration cycle.

At generator and evaporator, the working fluid change to vapor phase at generating temperature T_g and evaporating temperature T_e , respectively. T_g and T_e strongly effect an efficiency of the cycle, and, the configurations of ejector

also effect to the cycle performance.

For the purpose of measuring the ability of the cycle, in door testing device is set up. Using this device, it is possible to confirm the actual performance of the cycle and clarify the individual performance of designed ejector itself under stable conditions. Figure 4 shows schematic diagram of a whole set of test equipment. As heat source for generator, hot water from Isothermal bath I is used, although the generator heat source is supplied by solar collector panel in the actual case.

There are two ejectors in the testing device, one is the ejector that is a part of an ejector refrigeration cycle, another is designed to use for enhancing lower pressure condition in evaporator. The latter is not used in this study.

The working fluid is HFC-134a ($\text{CH}_2\text{F}-\text{CF}_3$), this is determined based on the thermodynamic properties of many working fluids, including HFC-134a as explained in another paper [1].

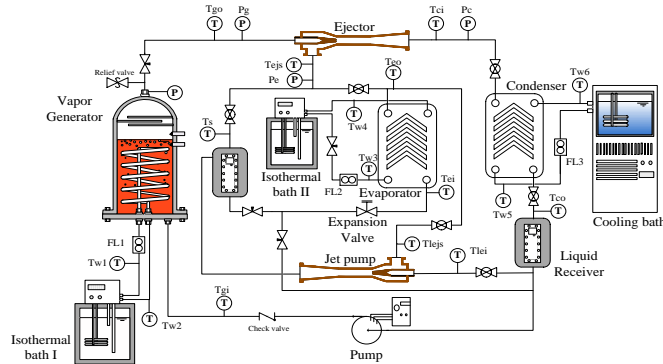


Fig. 4: Schematic diagram of test equipment.

The working fluid, HFC-134a is heated in a generator or an evaporator by heat exchanging with water. Thermal input to the generator and the absorbed heat in the evaporator is estimated by measuring the water flow-rate and the temperature change between inlet and outlet.

Thermal input to vapor generator, Q_g , is defined as the thermal energy consumption in an ejector refrigeration cycle, and absorbed heat in evaporator, Q_e , is defined as cooling capacity of the cycle. The coefficient of performance (COP) is defined by equation (1).

When performing experiments, the COP is measured by changing condensing temperature T_c under the conditions of T_g and T_e being constant. T_g , T_e and T_c are used as the respective saturation temperatures.

$$\text{COP} = \frac{Q_e}{Q_g} \quad (1)$$

The more details of this testing device are explained in the previous reports [1] and [2].

2.2 Ejector

An ejector is the most important part in an ejector refrigeration cycle, and COP of this cycle depends on the configuration design of ejector. The ratio of flow rates of the primary flow to the secondary flows is defined as an entrainment ratio ω .

There is a relationship between COP and ω , which is equation (2), where Δh stands for the change in specific enthalpy, and subscript 'e' and 'g' stand for evaporator and generator, respectively.

$$\text{COP} = \omega \times \frac{\Delta h_e}{\Delta h_g} \quad (2)$$

Equation 2 implies that COP is proportional to entrainment ratio when T_g and T_e are constant. Therefore, the entrainment-ratio increase directly results of the efficiency increase of an ejector refrigeration cycle.

Chan et al. have conducted the analytical approach and optimized the configuration design of an ejector [1], [2].

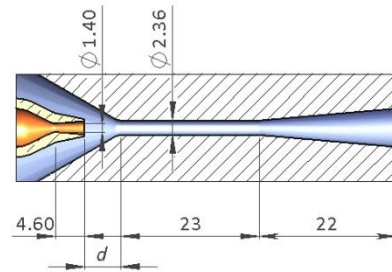


Fig. 5: Ejector important dimensions mm.

Figure 5 shows some important dimensions of the ejector used in the test equipment, which is designed based on the analysis carried by Chan et al. The theoretical predictions of these dimensions were reported in Chan et al. 2011.

On the basis of this analysis, Chan et al [1] and [2] Fukushima et al [3] have made the experimental setup including the ejector shown in figure 4 and have performed experiments for evaluation. The ejector is called as "Ejector A".

Ito et al. [4] have conducted a numerical analysis to compressible fluid flow in an ejector as a computational fluid dynamics, CFD.

According to the CFD result, the entrainment ratio is estimated as being more than double if the mixing section area increases about 160 % [4]. This ejector is called as “Ejector B”

2.3 Experimental Results

Based on Ito’s study, Ejector B is made as the mixing section area being larger than Ejector A by 60 %.

Using Ejector B in the experimental system, the results are shown as follow.

Figure 6 shows the experimental results on the condition of $T_g = 69\text{ }^\circ\text{C}$ and $T_e = 15\text{ }^\circ\text{C}$. While condensing temperature is below $23.5\text{ }^\circ\text{C}$, COP is constant. However, when T_c becomes higher than $23.5\text{ }^\circ\text{C}$, the COP decreases drastically. This transition temperature is called as “critical condensing temperature T_c^* ”, which is $23.5\text{ }^\circ\text{C}$ in case of Figure 6, when $T_g = 69\text{ }^\circ\text{C}$ and $T_e = 15\text{ }^\circ\text{C}$, T_c^* is $23.5\text{ }^\circ\text{C}$.

Condenser temperature has to be below T_c^* , in order to operate an ejector refrigeration cycle stably. As T_g and T_e changes, T_c^* also changes. And the configuration design of ejector influences on T_c^* strongly.

The performance of the cycle in this study is obtained as a function of generating and evaporating temperatures. Figure 7 shows the relationship between COP and T_g at $T_e = 10$ and $15\text{ }^\circ\text{C}$. This indicates that the higher T_g makes lower COP in the case of Ejector B.

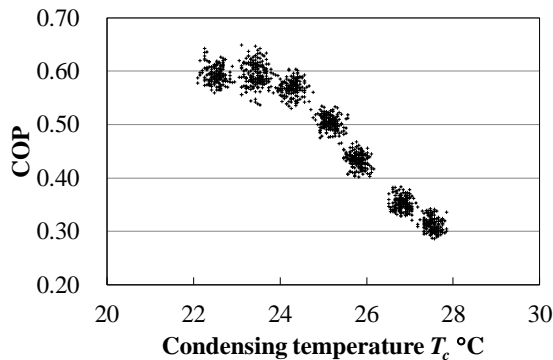


Fig. 6: Experimental result at $T_g = 69\text{ }^\circ\text{C}$ and $T_e = 15\text{ }^\circ\text{C}$.

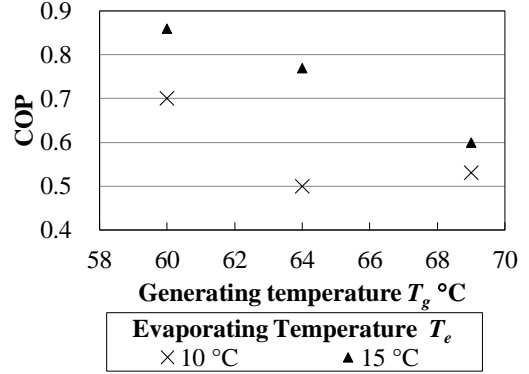


Fig. 7: Relationship between COP and T_g .

Figure 8 shows the relationship between critical condensing temperature T_c^* at different T_g with $T_e = 10$ and $15\text{ }^\circ\text{C}$. This implies that T_c^* cannot be a simple function of T_g .

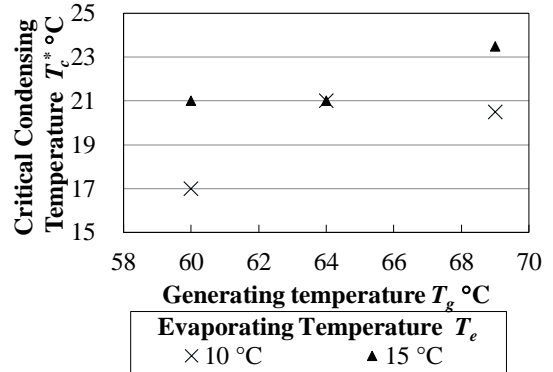


Fig. 8: Relationship between T_c^* and T_g .

2.4 Comparison between two ejectors

Fukushima et al. experimentally evaluated an ejector refrigeration cycle with Ejector A [3].

The evaluation result will be reported in this paper under the common condition for the case of Ejector B.

Figure 9 shows the experiment results comparison between Ejectors A and B at $T_g = 69\text{ }^\circ\text{C}$ and $T_e = 15\text{ }^\circ\text{C}$. The COP using Ejector B is about double as much as the case using Ejector A. On the other hand, T_c^* is lower by about $10\text{ }^\circ\text{C}$, at $T_g = 69\text{ }^\circ\text{C}$ and $T_e = 15\text{ }^\circ\text{C}$

Figures 10 and 11 show the comparison about COP and T_c^* between Ejectors A and B for two different condition of T_g and T_e . The COP in case of using Ejector B in the cycle is always about double compared to the case using Ejector

A, and the critical condensing temperature of Ejector B is lower by 10 °C compared to the case using Ejector A.

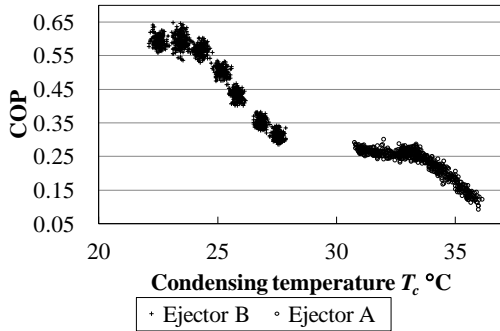


Fig. 9: Comparison between Ejectors A and B about COP at $T_g = 69$ °C and $T_e = 15$ °C.

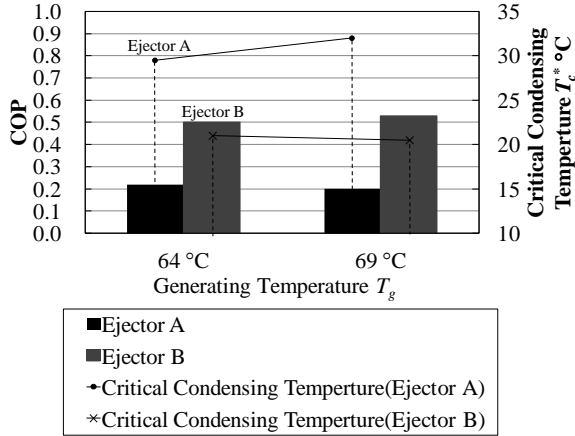


Fig. 10: Comparison between Ejectors A and B about COP and T_c^* in case of $T_e = 10$ °C.

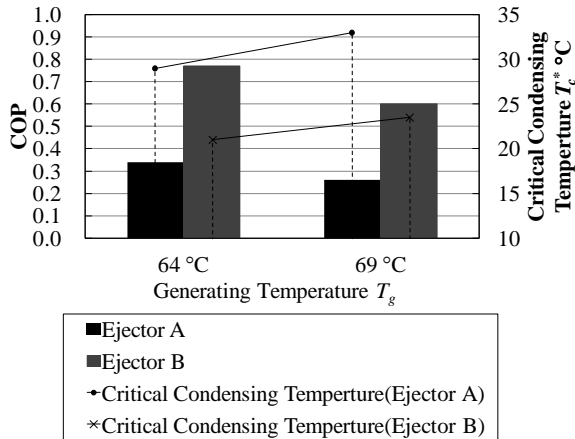


Fig. 11: Comparison between Ejectors A and B about COP and T_c^* in case of $T_e = 15$ °C.

3. EXERGY

Exergy efficiency is important in the evaluation of refrigerating cycle. Exergy efficiency of ejector refrigeration cycle using ejector B was evaluated. Exergy efficiency of ejector refrigeration cycle η_E is calculated in equation (3)

$$\eta_E = \frac{A_e}{A_g + W} \quad (3)$$

Power consumption in pump, W , is assumed to be equal to the exergy consumption. Therefore, W cannot be ignored. Exergy A is calculated by equation (4) and W is by equation (5), where h stands for specific enthalpy, subscript 'c' stand for condenser, and subscript 'i' and 'o' each stand for inlet and outlet.

$$A = Q \left(1 - \frac{T_0}{T} \right) \quad (4)$$

$$W = \frac{m_p (h_{gi} - h_{co})}{\eta_p} \quad (5)$$

' m_p ' and ' η_p ' each stands for 'mass flow rate in pump' and 'efficiency of pump'

Efficiency of the pump, which is used in the experimental set up, is 0.85

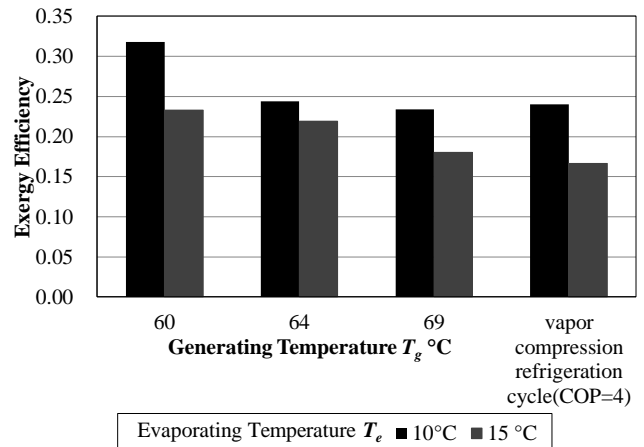


Fig. 12: Exergy efficiency of an ejector refrigeration cycle and vapor compression refrigeration cycle.

Figure 12 shows Exergy efficiency at $T_g = 60$ °C, 64 °C, and 69 °C with vapor compression refrigeration cycle's efficiency (COP=4). Exergy efficiency of vapor

compression cycle is calculated by Equation (6). In this equation, T is regarded as T_e .

$$A = \text{COP} \times \left(1 - \frac{T_0}{T}\right) \quad (6)$$

Exergy efficiency of ejector refrigeration cycle is as much as that of vapor compression refrigeration cycle.

4. CONCLUSION

In order to establish an ejector refrigeration cycle for utilizing solar thermal energy, cycle capacity and performance were experimentally evaluated. In this evaluation, the high performance ejector configuration, which is designed on the basis of the numerical analysis of CFD, was experimentally confirmed. The maximum efficiency was beyond 80 % at a certain temperature combination.

COP greater than 50 % is always accomplished at $T_g = 60$ °C, 64 °C, and 69 °C with $T_e = 10$ °C and 15 °C in this cycle.

The evaluation also made it approved that the performance of an ejector refrigeration cycle is strongly influenced by the configuration design of ejector.

Exergy efficiency η_E was also evaluated, and η_E of ejector refrigeration cycle is as much as that of vapor compression refrigeration cycle's efficiency (COP=4).

In conclusion, positive possibility to develop a high performance ejector refrigeration cycle, which is designed on the basis of analytical, numerical, and experimental approaches, was confirmed in this study.

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