

# Study on Improving the Performance of the Cascade Heat Pump Cycle using Ejectors

S. W. Jang<sup>1</sup> and Y. L. Lee<sup>2\*</sup>

<sup>1</sup>Department of Mechanical Engineering, Kongju National University, Gongju-si, Chungcheongnam-do, Korea; swjang@kongju.ac.kr

<sup>2</sup>Department of Mechanical and Automotive Engineering, Kongju National University, Gongju-si, Chungcheongnam-do, Korea; ylee@kongju.ac.kr

## Abstract

**Background:** The cascade heat pump cycle is used when a large difference between the condensing temperature and the evaporating temperature exist. **Methods:** This study uses ejectors to improve the performance of a cascade heat pump cycle that utilizes refrigerants R134a and R404a. Ejectors were applied to the high-stage cycle, the low-stage cycle and then to both cycles. Changes in performance according to the condensing temperature, evaporating temperature and ejector entrainment ratio were tracked. **Results:** Results of the numerical analysis showed that applying ejectors to both the high-stage and low-stage cycles provided the greatest efficiency, yielding a 26.9% increase in the COP compared to standard cascade cycles. **Conclusion:** For COP enhancement, it is beneficial to apply ejectors to both-stage cycles as well as to lower the ejector entrainment ratio as much as possible.

**Keywords:** Cascade, COP, Ejector, Heat Pump, Refrigerator

## 1. Introduction

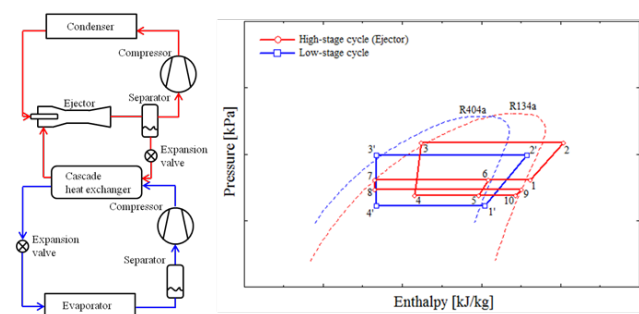
The Coefficient of Performance (COP) drops significantly when the evaporating temperature is extremely low in a single-stage refrigeration cycle<sup>1</sup>. To address this issue, Shin, et al.<sup>2</sup> carried out a performance analysis of a two-stage compression cycle, while Lee, et al.<sup>3</sup> examined the benefits of two phase refrigerant injection. Natarajan, et al.<sup>4</sup> investigated the performance of Joule-Thomson refrigeration system with environment friendly refrigerant mixture, Yan, et al.<sup>5</sup> used the refrigerant mixture R290/R600a to enhance the performance of an auto-cascade refrigeration cycle. The cascade heat pump cycle offers the advantage of a higher COP than existing heat pump cycles, where the difference between the condensing temperature and evaporating temperature is high. This study utilizes an ejector, instead of the conventional

expansion valve, to enhance the performance of the cascade heat pump cycle.

The ejector sprays liquid refrigerant from the nozzle. The pressure of the sprayed refrigerant is raised by a diffuser and the resulting high pressure gas refrigerant is fed into the compressor. The remaining liquid refrigerant is separated by a separator and sprayed once more using an expansion valve. This results in a lower evaporating temperature and the change in the mass flow caused by the ejector reduces the compression load, thus enhancing the COP. There is active research ongoing in the application of ejectors to refrigeration systems and heat pump systems utilizing this principle. Yun<sup>6</sup> conducted a study on improving the performance in a refrigeration system installed with an ejector entraining expanded gases, while Wang, et al.<sup>7</sup> carried out a performance analysis of a heat pump cycle installed with an ejector.

\*Author for correspondence

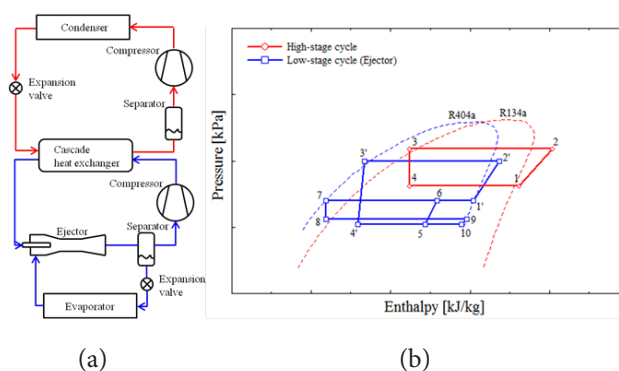
This study aims to enhance the COP in the existing cascade heat pump cycle by applying ejectors to the high-stage cycle, the low-stage cycle and both cycles. It also aims to optimize the performance of the cascade heat pump cycle according to changes in the condensing temperature, evaporating temperature and ejector entrainment ratio.



**Figure 1.** Schematic and P-h diagrams of the high-stage ejector cycle.

## 2. Numerical Methods and Analysis Conditions

We designed an ejector to enhance the COP of the cascade heat pump cycle and applied it to the high-stage cycle and low-stage cycle separately. The widely used software EES<sup>8</sup> was used to analyze our results. The refrigerant R134a was used in the high-stage cycle while R404a was used in the low-stage cycle. The isentropic efficiency of the compressor was assumed to be 0.75, while the compressor discharge mass flow in the high-stage cycle was assumed to be 1 kg/s. Figure 1 and Figure 2 are schematic diagrams of the cascade heat pump cycle installed with the ejector. Figure 1 shows the ejector applied at the high-stage cycle while Figure 2 shows the ejector applied at the low-stage cycle. Table 1 presents the conditions for the cycle analysis. In the high-stage cycle, the condensing temperature was set at 55 °C, while the low-stage cycle evaporating temperature was -35 °C. The cascade temperature difference was 5 °C. Under these conditions, the enhancement of the COP in a cascade heat pump cycle installed with an ejector compared to the existing cascade was measured and analyzed. At the same time, changes in the COP according to the condensing temperature, the evaporating temperature and the mass flow as a function of the ejector entrainment ratio were analyzed.



**Figure 2.** Schematic and P-h diagrams of the low-stage ejector cycle. (a) Schematic diagram. (b) P-h diagram.

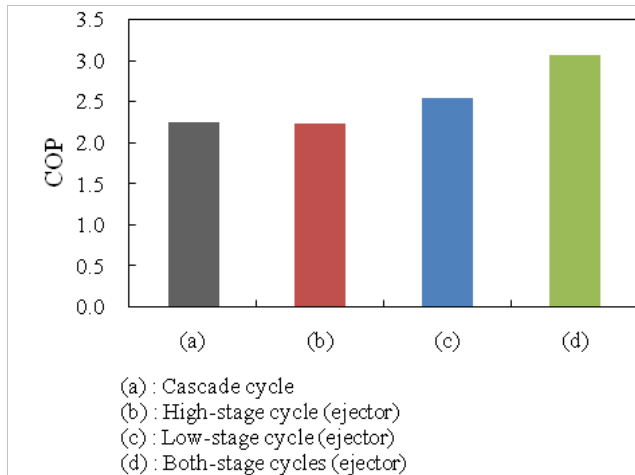
**Table 1.** Cycle analysis conditions

| Parameter                                   | Value           |
|---------------------------------------------|-----------------|
| Condensing temperature in high-stage cycle  | 35 °C ~ 65 °C   |
| Evaporating temperature in high-stage cycle | 10 °C           |
| Condensing temperature in low-stage cycle   | 15 °C           |
| Evaporating temperature in low-stage cycle  | -55 °C ~ -25 °C |
| Compressor efficiency                       | 0.75            |

## 3. Results and Discussion

### 3.1 Change in COP according to Ejector Location

Figure 3 shows the COP according to the ejector location when the high-stage cycle condensing temperature is 55 °C, the low-stage cycle evaporating temperature is -35 °C, the cascade temperature difference is 5 °C and the ejector entrainment ratio is 0.75. Figure 3(a) is the COP of the existing cascade cycle, Figure 3(b) is the COP when the ejector is applied to the high-stage cycle, Figure 3(c) is the COP when the ejector is applied to the low-stage cycle and Figure 3(d) is when ejectors are applied to both cycles. The COP is 2.236 in Figure 3(a) and 2.231 in Figure 3(b), showing a 0.22% decrease. This shows that when the ejector is applied to the high-stage cycle, the change in the COP is minimal while there is a decrease in the compressor mass flow due to the ejector, leading to lower heat dissipation and in turn resulting in a lowered COP compared to the existing cascade cycle. The COP in Figure 3(c) is 2.537, showing an increase of 11.7% over the existing cascade cycle. In Figure 3(d), the COP is 3.062, 26.9% higher than the existing cascade cycle. Therefore,

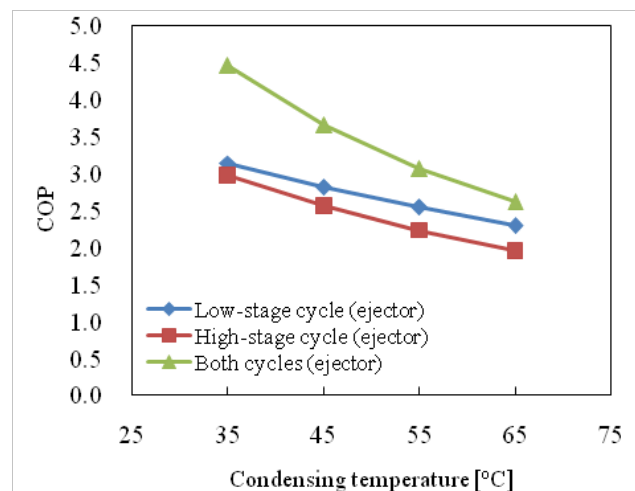


**Figure 3.** Change in COP according to ejector location.

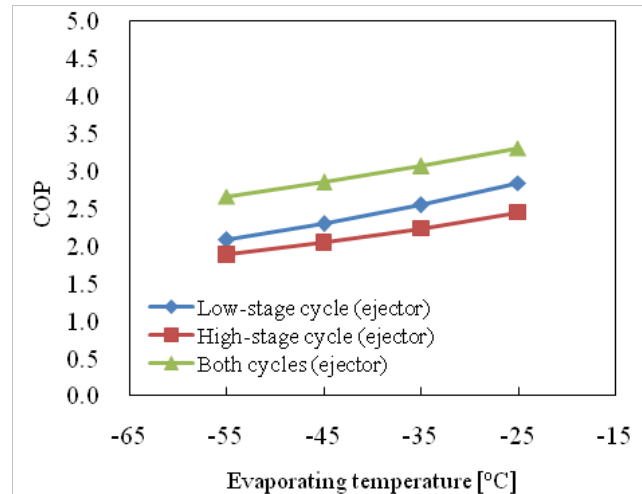
the results show that installing ejectors in both cycles offers the greatest efficiency when using ejectors in the cascade heat pump cycle.

### 3.2 Change in COP according to Condensing Temperature and Evaporating Temperature

The application of ejectors in the high-stage cycle and low-stage cycle individually, as well as in both cycles simultaneously was examined to verify the effects of condensing and evaporating temperatures. The ejector entrainment ratio was set at 0.75, while the condensing temperature was varied from 35 °C to 65 °C and the evaporating temperature from -55 °C to -25 °C. Figure 4 shows the change in COP according to condensing temperature. In all three



**Figure 4.** Change in COP according to condensing temperature.



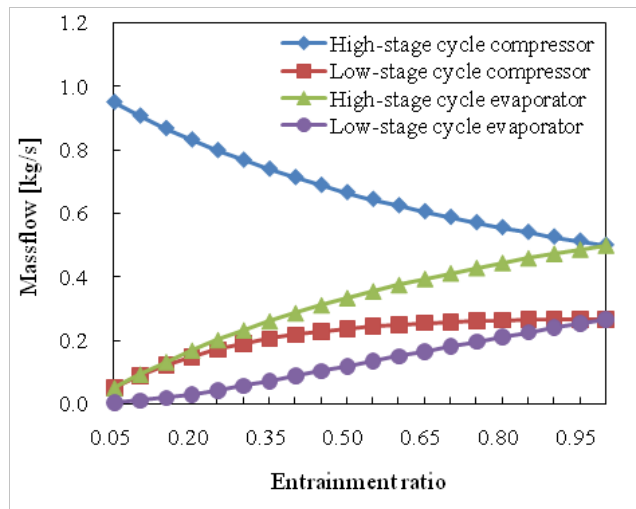
**Figure 5.** Change in COP according to evaporating temperature.

cases, as the condensing temperature rose, the COP fell, as higher condensing temperature means a higher compression load. The decline in the COP according to the condensing temperature is steepest when ejectors are applied in both cycles. This can be attributed to a greater change in the heat dissipated by the condenser compared to the change in the compression load.

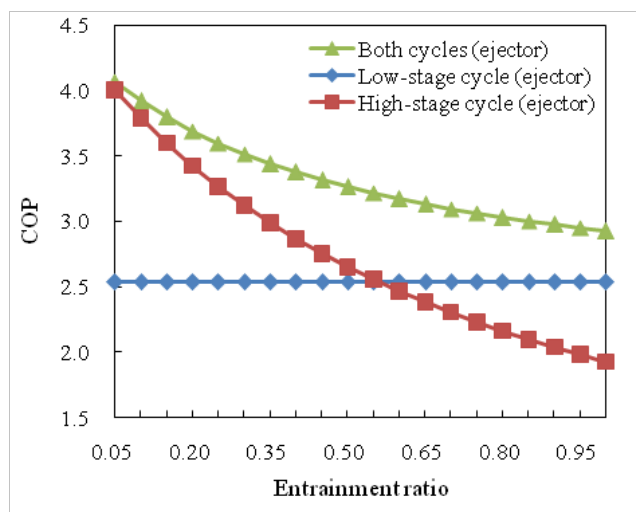
Figure 5 shows the change in the COP according to the evaporating temperature. When the evaporating temperature decreases, the compression load increases, leading to a decrease in the COP. In the case with the highest COP, where ejectors are installed at both cycles, it can be seen that the COP is affected more by the condensing temperature than by the evaporating temperature.

### 3.3 Performance Analysis of Cascade Heat Pumpcycle according to Ejector Entrainment Ratio

As the performance of the heat pumpcycle is greatly affected by the entrainment ratio of the ejector, the entrainment ratio was varied between 0.05 and 1. Figure 6 shows the mass flow at each component according to the entrainment ratio, when ejectors are applied to both cycles. In the high-stage cycle, the discharged mass flow at the compressor increases when the entrainment ratio decreases, causing the amount of dissipated heat to rise. In the low-stage cycle, the mass flow at both the compressor and the evaporator decreases when the entrainment ratio decreases, resulting in a rise in the COP. Therefore, when ejectors are applied to both cycles of the cascade



**Figure 6.** Change in low-stage cycle and high-stage cycle mass flow according to entrainment ratio.



**Figure 7.** Change in COP according to entrainment ratio.

heat pumpcycle, it is best to lower the entrainment ratio as much as possible to optimize heat dissipation and enhance the COP.

Figure 7 shows the changes in the COP according to the ejector entrainment ratio when ejectors are installed in the high-stage cycle, low-stage cycle, and both cycles. When ejectors are applied at the high-stage cycle and both cycles, the COP decreases when the entrainment ratio increases. This is because the mass flow of the refrigerant into the evaporator increases while the mass flow of the refrigerant into the compressor decreases, resulting in lower heat dissipation. When the ejector is applied to the low-stage cycle, the change in the entrainment ratio has

almost no effect on the COP. This is because the COP is calculated using heat dissipation at the condenser and not heat absorption at the evaporator.

## 4. Conclusion

This study was conducted under the objective of enhancing the COP by applying ejectors to the existing cascade heat pumpcycle at the high-stage cycle and the low-stage cycle individually, as well as both cycles simultaneously. The conclusions of this study are as follows:

- When ejectors were applied to the existing cascade cycle in the high-stage cycle, the low-stage cycle and both cycles, the highest COP increase, 26.9%, was obtained when the ejector was installed in both cycles.
- When ejectors are installed at both cycles, the decline in the COP according to condensing temperature increase is relatively larger. This is due to the change in heat dissipation at the condenser being larger than the change in the compression load. Condensing temperature has a relatively larger influence on the COP compared to evaporating temperature.
- For heat dissipation and COP enhancement, it is more beneficial to lower the ejector entrainment ratio as much as possible when ejectors are applied to both cycles of a cascade heat pumpcycle.
- Finally, further experimental research should be conducted on the application of ejectors to the cascade heat pumpcycle.

## 5. Acknowledgements

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2011-0024805). In addition, this work was supported by the Human Resources Development program (No. 20134030200230) of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Trade, Industry and Energy.

## 6. References

1. Li W, Feng X, Yu L J, Xu J. Effects of evaporating temperature and internal heat exchanger on organic Rankine cycle. *Applied Thermal Engineering*. 2011 Dec; 31(17-18):4014–23.

2. Shin E, Park C, Cho H. Theoretical analysis of performance of a two-stage compression CO<sub>2</sub> cycle with two different evaporating temperatures. *International Journal of Refrigeration*. 2014 Aug; 47:164–75.
3. Lee H, Hwang Y, Radermacher R, Chun H. Potential benefits of saturation cycle with two-phase refrigerant injection. *Applied Thermal Engineering*. 2013 Jul; 56(1-2):27–37.
4. Natarajan V, Vanitha S. Performance investigation of Joule-Thomson Refrigeration System with Environment Friendly Refrigerant Mixture. *Indian Journal of Science and Technology*. 2015 May; 8(S9):465–73.
5. Yan G, Hu H, Yu J. Performance evaluation on an internal auto-cascade refrigeration cycle with mixture refrigerant R290/R600a. *Applied Thermal Engineering*. 2015 Jan; 75:994–1000.
6. Yun S. Theoretical study on the performance improvement of refrigeration system installed with ejector entraining expansion gases after expansion process. *Journal of the Korean Society of Marine Engineering*. 2014 Sep; 38(7):823–33.
7. Wang X, Yu J, Xing M. Performance analysis of a new ejector enhanced vapor injection heatpump cycle. *Energy Conversion and Management*. 2015 Aug; 100:242–8.
8. Klein SA. *Engineering Equation Solver (EES). F-Chart Software*. Commercial V9. 100-3D 2012.