

Ejector Energy-Saving Technology for Mobile Air Conditioning Systems

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ABSTRACT

This study reports on a new generation ECS (Ejector Cycle System) which includes a highly efficient ejector and a novel system configuration. The ejector is working as a fluid jet pump that recovers expansion energy which is wasted in the conventional refrigeration cycle decompression process, and converts the recovered expansion energy into pressure energy and raises the compressor suction pressure. Consequently, the ejector system can reduce power consumption of the compressor by using the above mentioned pressure-rising effect and improve energy efficiency of the refrigeration cycle. The ejector consists of a nozzle, a suction section, a mixing section and a diffuser. The objective of this study is to improve actual fuel economy of all vehicles by ejector technology. The previous generation ECS was reported in 2012 SAE World Congress¹. Now, a new generation ECS has been successfully developed and released in the market for Mobile Air Conditioning systems as of 2013. It achieves higher energy efficiency through the development of ARC (Active flow Ratio Control. It means to control the refrigerant flow ratio of the suction flow to the total flow by separating gas-liquid two phase flow), improved design of each ejector part, and improved internal flow distribution inside the evaporator. The ejector is integrated into the tank of evaporator like the previous generation, so there is no impact to vehicle packaging space. Test results demonstrated that the new generation ECS reduced annual power consumption of compressor by 10% compared to previous generation and by 20% compared to conventional expansion valve systems. The new generation ejector technology can significantly improve actual fuel consumption of Mobile Air Conditioning systems and contribute to global greenhouse gas reduction.

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INTRODUCTION

In order to meet the future needs of CO₂ emissions reduction and energy conservation, DENSO has applied ejector technologies on varieties of HVAC&R products in both automotive and residential industries^{2, 3-4} (shown in Figure 1). In the automotive industry, approaches to improve actual fuel economy and electric power consumption including mobile air conditioning systems has been studied all over the world toward 2020. Due to these circumstances, improving the efficiency of the air conditioning system has been a focus for many years. DENSO introduced the first generation of ECS evaporators with integrated ejector to global market since 2009. This product had great energy saving effect at that time, but regulations of CO₂ emissions become increasingly strict year after year all over the world. For example in Europe, over 30% reductions in CO₂ emissions compared with 2012 are required in 2020. We therefore developed a new generation ECS which achieved higher energy saving effect, and released in the market for Mobile Air Conditioning systems in 2013.

In this paper, outline of previous generation ECS (Ejector Cycle System) and principle of ejector are explained at first. Then, outline of new generation ECS and improved technologies are explained in detail. Finally, the performance result of new generation ECS and summary are described.

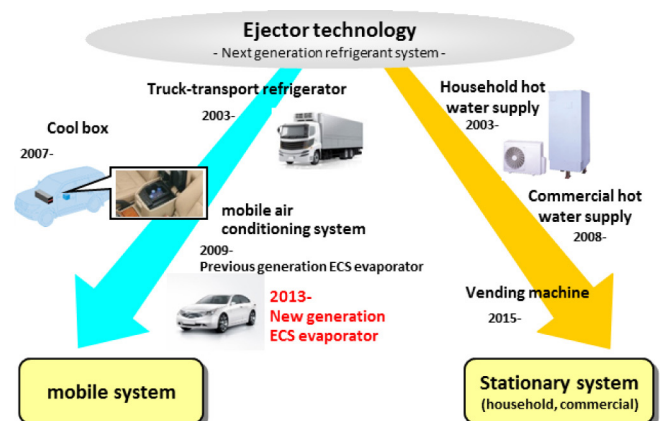


Figure 1. Variety of products using ejector technology

1. PREVIOUS GENERATION ECS (EJECTOR CYCLE SYSTEM)

1-1 Overview of ECS and ECS Evaporator

First of all, Figure 2 shows the photo of the previous generation ECS evaporator and the ejector. The ejector is placed inside the top tank of the evaporator and integrated into the evaporator. The system configuration is same as conventional AC system (shown in Figure 3) except for that regular evaporator is replaced by ECS evaporator, as shown in Figure 4.

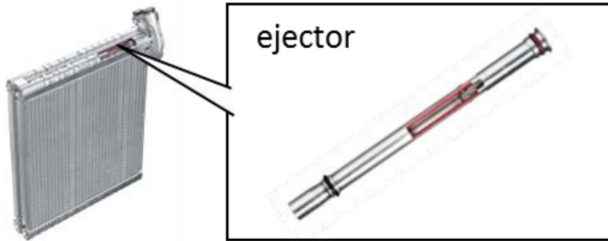


Figure 2. Photo of the previous ECS evaporator and the ejector

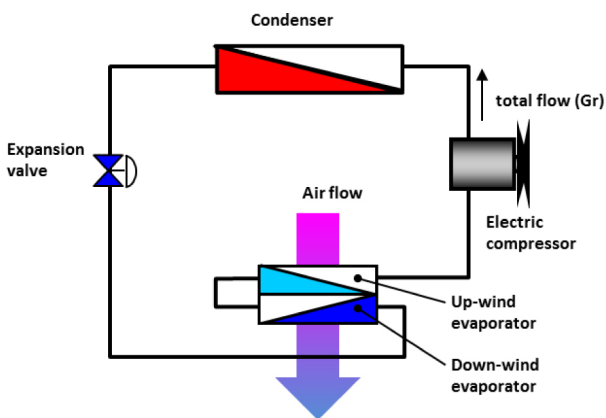


Figure 3. Conventional system configuration

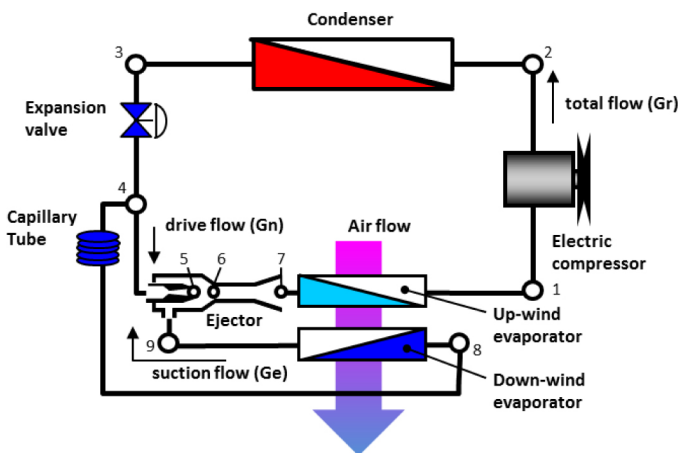


Figure 4. Previous generation ECS (Ejector Cycle System) configuration

As seen from Figure 4, the ECS splits the evaporator into two; an upwind evaporator and a down-wind evaporator. The expansion valve used after the condenser expands refrigerant just into the two-phase region. The refrigerant flow after the expansion valve is divided and

run into the ejector (Drive flow: G_n) and the capillary tube (Suction flow: G_e). The suction flow which passes through the down-wind evaporator is suctioned by the ejector and mixed together with the drive flow. The mixed flow passes through up-wind evaporator and runs into the compressor.

Figure 5 shows the refrigerant behavior of ECS by the p-h diagram compared with a conventional cycle. The expansion valve in the ejector cycle is mainly used to adjust refrigerant flow to make sure there is positive SH (degree of super heating) at the exit of the upwind evaporator so no liquid refrigerant enters the compressor.

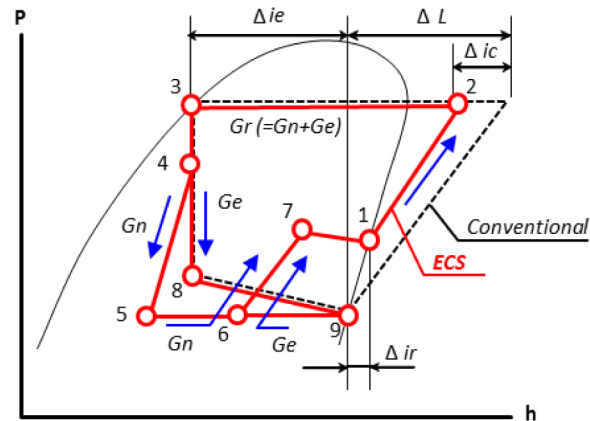


Figure 5. Refrigerant behavior of ECS by the p-h diagram compared with a conventional cycle.

The energy saving effect of ejector cycle is explained below. COP is used as an indicator to show the efficiency of a refrigerant cycle, which is the ratio of cooling performance (Q_{conv}) to compressor power consumption (L_{conv}), and can be expressed as,

$$Q_{conv} = G_r \cdot \Delta ie \quad (1)$$

$$L_{conv} = G_r \cdot \Delta L \quad (2)$$

Thus,

$$COP_{conv} = \frac{Q_{conv}}{L_{conv}} = \frac{\Delta ie}{\Delta L} \quad (3)$$

On the other hand, COP of ECS is noted by

$$Q_{ECS} = (G_n + G_e) \cdot (\Delta ie + \Delta ir) \quad (4)$$

$$L_{ECS} = (G_n + G_e) \cdot (\Delta L - \Delta ir - \Delta ic) \quad (5)$$

Thus,

$$COP_{ECS} = \frac{\Delta ie + \Delta ir}{\Delta L - \Delta ir - \Delta ic}$$



Δi_r : refrigerant enthalpy difference at evaporator outlet

Δi_c : refrigerant enthalpy difference at compressor outlet

And so using equation (3) and (6), COP improvement effect by ejector cycle is as follows,

$$\frac{COP_{ECS}}{COP_{conv}} = \left(1 + \frac{\Delta i_r}{\Delta i_e}\right) \cdot \left(\frac{1}{1 - \frac{\Delta i_r + \Delta i_c}{\Delta L}}\right) \quad (7)$$

The evaporator outlet pressure raise by ejector increases as ejector efficiency increases. And it results in increased Δi_r and Δi_c , and improved COP over conventional cycle as shown by equation (7). It means that the higher the ejector efficiency, the more the COP improvement. Furthermore, it is expected in actual use that the pressure raise of the ejector will lower the compression ratio of compressor and improve the compressor efficiency.

Figure 6 shows the annual energy saving effect of previous generation ECS based on test results. The ejector system with ECS evaporator achieved 10% power saving compared to the conventional expansion valve system.

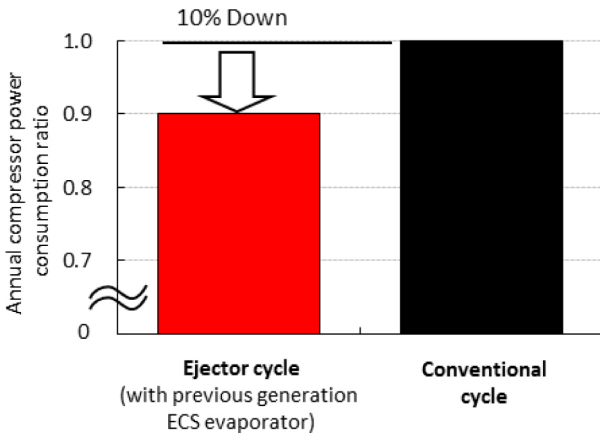


Figure 6. Bench test result of annual compressor power consumption

1-2 Details of Ejector

As shown in Figure 7, the ejector consists of a nozzle, a mixing section, a diffuser, and a suction section. The gas-liquid two phase refrigerant flowing into the nozzle (Drive flow: G_n), is accelerated and decompressed in the nozzle to a pressure lower than the pressure of down-wind evaporator outlet (P_L). This pressure difference ($P_L - P_s$) generates the intake flow (Suction flow: G_e). The drive flow which is accelerated to supersonic flow by the nozzle and the suction flow which is subsonic are mixed at the mixing section, and the mixed flow is gradually decelerated with increase of refrigerant pressure at the diffuser.

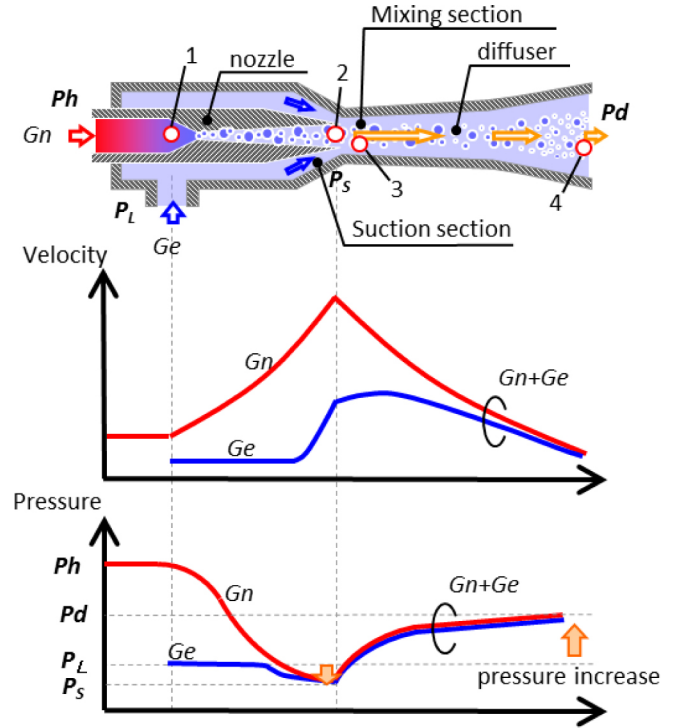


Figure 7. Structure of the Ejector and Refrigerant behavior in the ejector

As an indicator of the energy conversion efficiency of the ejector, η_{eje} (the ejector efficiency) is introduced here. This efficiency shows the ratio of recovered pressure energy by the ejector to pressure energy which the drive flow has at inlet of the nozzle. Using η_{noz} as the efficiency of nozzle and η_{dif} as the efficiency of mixing section and diffuser, the ejector efficiency η_{eje} can be expressed as,

$$\eta_{eje} = \eta_{noz} \cdot \eta_{dif} \quad (8)$$

η_{noz} represents the efficiency of nozzle converting pressure energy to kinetic energy,

$$\eta_{noz} = \frac{\int_1^2 d\left(\frac{v^2}{2}\right)}{\int_1^2 \frac{dP}{\rho}} \quad (9)$$

*suffix 1 indicates nozzle inlet; suffix 2 indicates nozzle outlet

Meanwhile, η_{dif} represents the efficiency of diffuser converting kinetic energy to pressure energy,

$$\eta_{dif} = \frac{\int_3^4 \frac{dP}{\rho}}{\int_3^4 d\left(\frac{v^2}{2}\right)} \quad (10)$$

*suffix 3 indicates mixing section inlet; suffix 4 indicates diffuser outlet