# APPLICATION OF HEAT PUMP SYSTEM FOR ECO-FRIENDLY VEHICLES

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**Abstract:** The market of eco-friendly vehicles developed by manufacturers worldwide is expected to expand to 3 million vehicles by 2020. The main issue with these vehicles is the limitation of the driving range when using the heating system. The purpose of this study is to decrease the amount of energy consumed by the heating system by applying a heat pump system. We have developed some highly efficient heat pump systems that make up for vehicle heat loss including heat from the drive motor and warmed cabin air. One of these heat pump systems is able to run continuously and maintain stable operation even in lower ambient temperature conditions. We verified that this heat pump system has improved the electric power efficiency by 10% to 60% in comparison to the current heating system. It is also foreseen that this system will contribute to extending the driving range of the vehicle.

**Key Words: automobile, recover, mileage**

## 1 INTRODUCTION

Due to the recent rise in environmental awareness, the market of the eco-friendly vehicles such as electric vehicles (EV), hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles is expected to expand in near future. However, eco-friendly vehicles have not become as popular as expected mainly because of limited mileage, high cost of the vehicle and infrastructure issue. As for the mileage issue due to their limited battery capacity, it is expected to extend the driving range by incorporating a high efficiency air conditioning system for these eco-friendly vehicles. For EV, the driving mileage drops significantly when the heating system is operated. This thesis presents the current research developments of highly efficient heat pump systems which utilize the vehicle's exhausted heat or the heat from the outside air. Furthermore, future prospects for heating systems will be covered.

## 2 CURRENT SITUATION AND ISSUES

Vehicles which have an internal-combustion engine have a water circuit connected to their power train cooling system. This circuit is also linked to the cabin to create a heating system which uses exhausted heat from the engine. In the case of EV, the amount of exhausted heat from the driving motor or electric devices is much lower than that of gasoline engine

vehicles; therefore, this heat is not sufficient for the heating system. To make up for this disadvantage, an electric heater is added to the water circuit to make the water hot enough to operate the heating system (see Figure 1). On the other hand, this heating system has an issue with shortening mileage because its efficiency (COP) is less than 1. In other words, the electric energy of the current heating system consumes a large majority of the vehicle's total electric energy when the heating system is operated (see Figure 2). As a result, there is an increasing demand to reduce the electric energy of the heating system when being operated. Highly efficient heat pump systems could be one of the solutions for this issue.

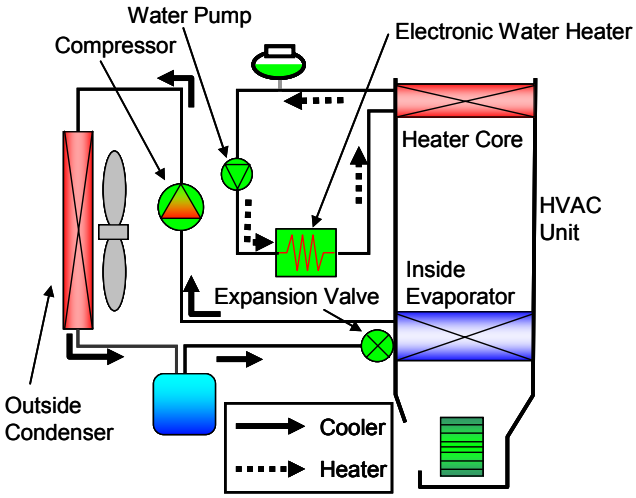



**Figure 1: Electric Heater System**

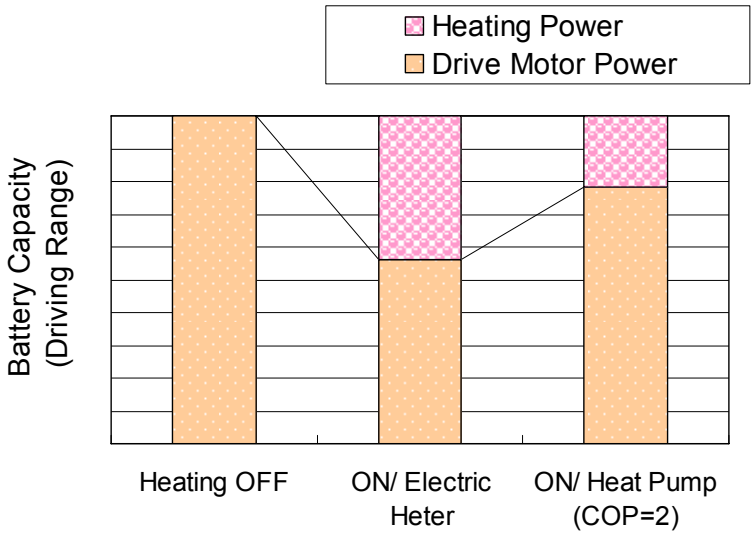



**Figure 2: Energy Consumption of EV Battery**

## 3 APPLICATION OF HEAT PUMP SYSYTEM INTO ECO-FRIENDLY VEHICLES

To overcome this issue, the decision to apply a heat pump system into the eco-friendly vehicles was made since the heat pump system consumes less electric power than the electric heater system.

### 3.1 Selection of Heat Source

Since the performance of the heat pump system is affected by the heat source, selection of the heat source needs to be made with careful consideration. The development of the heat pump systems based on the following heat sources:

- Heat energy in the outside air
- Heat energy from the ventilation air in the cabin

### 3.2 Outline of Heat Pump System

#### 3.2.1 Heat Pump System Using Outside Air Heat Source (System A)

This heat pump system absorbs the heat from the outside air and that heat is transferred to the cabin air using a refrigeration cycle. This heat pump system consists of an electric compressor, an inside condenser, a 3-way valve, a receiver, an expansion valve, an outside evaporator, an inside evaporator, and an outside condenser. The refrigerant circuit and main component specifications are shown in Figure 3 and Table 1. The size of the component is decided by the packaging space of the test vehicle. The heating performance depends on the outside temperature, vehicle speed and climate condition. Therefore, it is important to evaluate the influence of these factors when the heat pump system which utilizes the heat from the outside air is applied. For example, frost formation occurs on the outside evaporator when the heat pump system is operated in low ambient condition. As a result, it is necessary to have a heat pump system which prevents frost formation on the outside evaporator to avoid decreasing heating performance and stopping the heating operation. Also, by making the high pressure refrigerant circuit and the low pressure refrigerant circuit independent, the existing plumbing parts which are designed based on current production specifications can be used.

**Table 1: Main Components of Heat Pump System A (Outside Air Heat Source)**

| No. | Components | Specifications |
|---|---|---|
| 1 | Electric Compressor | Scroll Type |
| 2 | Inside Condenser (For HVAC) | Aluminum, Multiflow type, Effective area: 0.024m$^2$ |
| 3 | Outside Evaporator | Aluminum, Multiflow type, Effective area: 0.086m$^2$ |
| 4 | Inside Evaporator (For HVAC) | Aluminum, Multiflow type , Effective area: 0.037m$^2$ |
| 5 | Outside Condenser | Aluminum, Multiflow type, Effective area: 0.099m$^2$ |

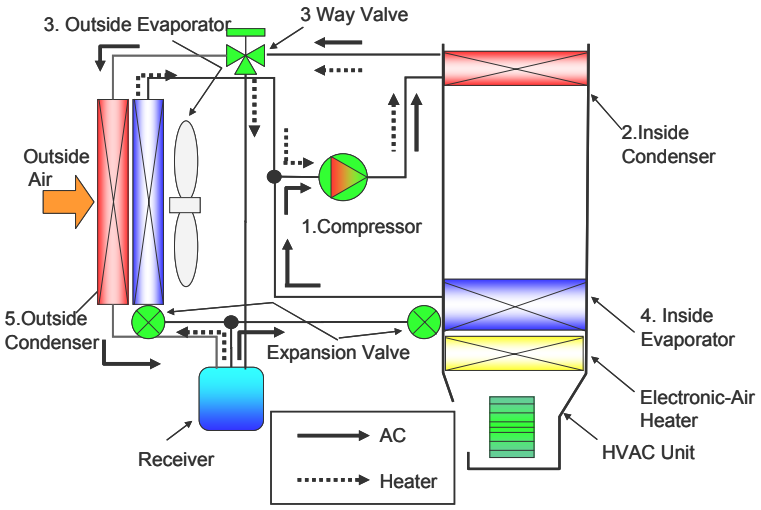



**Figure 3: Refrigerant Circuit of Heat Pump System A (Outside Heat Source)**

### 3.2.2 Heat Pump System Using Ventilation Exhausted Heat Source (System B)

This heat pump system absorbs the heat from the ventilation air in the cabin. This heat pump system consists of an electric compressor, an inside condenser, a 3-way valve, a receiver, an expansion valve, an inside evaporator, an outside condenser and a exhausted heat recovering unit. The refrigerant circuit and main component specifications are shown in Figure 4 and Table 3. The size of the component is decided by the packaging space of the test vehicle. The amount of heat absorbed from the ventilation air depends on the cabin temperature. In order to absorb enough heat from the ventilation air in the cabin even when the cabin is not warm in low ambient condition, both the HVAC unit and the exhausted heat recovering unit are equipped with air PTC heaters.

**Table 2: Main Components of Heat Pump System B (Ventilation Exhausted Heat Source)**

| No. | Components | Specifications |
|---|---|---|
| 1 | Electric Compressor | Scroll Type |
| 2 | Inside Condenser (For HVAC) | Aluminum, Multiflow type, Effective area: 0.024m$^2$ |
| 3 | Inside Evaporator (For HVAC) | Aluminum, Multiflow type, Effective area: 0.037m$^2$ |
| 4 | Inside Evaporator(For ventilation exhausted heat recovering unit) | Aluminum, Multiflow type , Effective area: 0.027m$^2$ |
| 5 | Outside Condenser | Aluminum, Multiflow type, Effective area: 0.099m$^2$ |

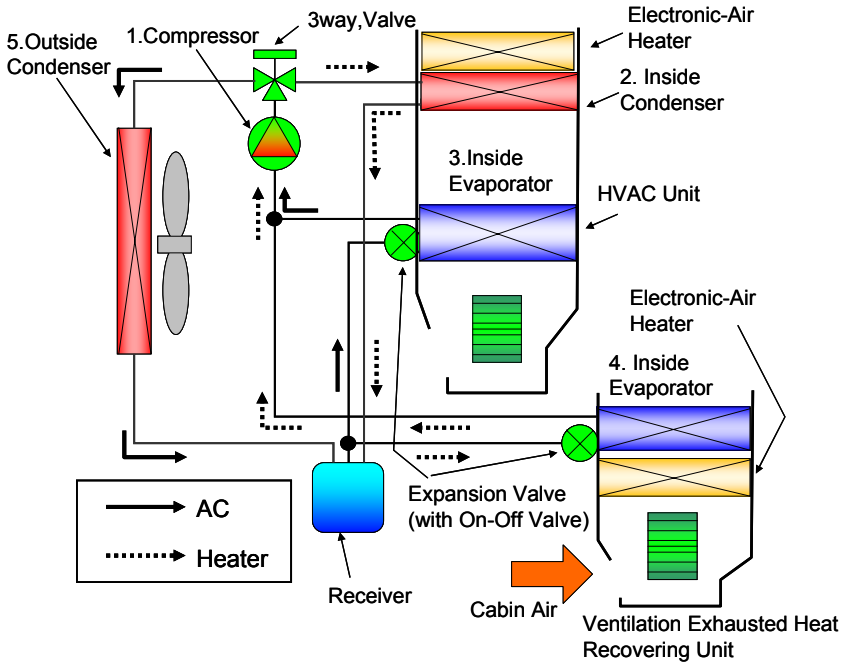



**Figure 4: Refrigerant Circuit of Heat Pump System B (Ventilation Exhaust Heated Source)**

## 3.3 Simulation

### 3.3.1 Heat Pump Simulation

To estimate the heat pump system performance, a heat pump simulation was conducted. This simulation is based on 1D analysis and performances calculated by the equations shown below. As for the refrigerant types, low pressure refrigerant (R134a) has been applied in this research due to refrigerant regulations, availability, and cost-effectiveness.

Evaporator Balance

Airside Cooling Performance

$$Q_{ea} = \phi \cdot G_{ea}\left(i_{aa} - i_{rr}\right) \quad (1)$$

Refrigerant side Cooling Performance

$$Q_{er} = \frac{V_c}{V_s}\left(i_a - i_d\right) \quad (2)$$

Balanced point

$$Q_{ea} = Q_{er} \quad (3)$$

$\phi$ : Enthalpy efficiency,
$G_{ea}$ : Air mass flow
$i_{aa}$ : Inlet air enthalpy
$i_{rr}$ : Saturated air enthalpy at refrigerant temp
$V_c$ : Compressor displacement
$V_s$ : Specific volume
$i_a$ : Inlet refrigerant enthalpy
$i_d$ : Outlet refrigerant enthalpy

Condenser Balance

Airside Condensing Performance

$$Q_{ca} = \phi_c \cdot C_a \cdot G_{ca}\left(T_{cr} - T_{ca}\right) \quad (4)$$

Refrigerant side Cooling Performance

$$Q_{cr} = \frac{V_c}{V_s}\left(i_b - i_c\right) \quad (5)$$

Balanced point

$$Q_{ca} = Q_{cr} \quad (6)$$

$\phi_c$ : Temperature efficiency,
$C_a$ : Air specific heat
$G_{ca}$ : Air specific heat
$G_{ca}$ : Air specific heat
$T_{cr}$ : Refrigerant temperature
$T_{ca}$ : Air inlet temperature
$i_a$ : Inlet refrigerant enthalpy
$i_d$ : Outlet refrigerant enthalpy

Compressor Driving Power

$$L_c = \frac{V_c}{V_s}\left(i_b - i_a\right) \quad (7)$$

COP (Coefficiency of Performance)

Cooling efficiency (AC)

$$COP_c = \frac{Q_{er}}{L} = \left( \frac{i_a - i_d}{i_b - i_a} \right) \quad (8)$$

Heating efficiency (Heat Pump System)

$$COP_h = \frac{Q_{cr}}{L} = \left( \frac{i_b - i_c}{i_b - i_a} \right) \quad (9)$$

If an additional electric heater is applied to the heat pump system, equation (10) is used to calculate its COP.

$$COP_h = \frac{Q_{cr}}{L_c + L_p} \quad (10)$$

$L_P$: Electric heater power

### 3.3.2 Heat Pump Simulation Results

The conditions of the heat pump simulation are shown in Table3.

**Table 3-1: Conditions of Heat Pump Simulation**

| | Simulation Conditions |
|---|---|
| | Heating Performance |
| Ambient temperature | -10, 0, 10 deg C |
| Target | Cabin temp: 25 deg C |
| Vehicle Speed | 40 km/h |

**Table 3-2: Airflow Rate/Temperature of Heat Pump System A**

| No. | Components | Airflow Rate / Temperature |
|---|---|---|
| 2 | Inside Condenser (For HVAC) | 2.3 [m/s] / -10,0,10 deg C |
| 3 | Outside Evaporator | 3.2 [m/s] / / -10,0,10 deg C |

**Table 3-3: Airflow rate of Heat Pump System B**

| No. | Components | Airflow Rate / Temperature |
|---|---|---|
| 2 | Inside Condenser (For HVAC) | 2.3 [m/s] / -10,0,10 deg C |
| 4 | Inside Evaporator(For ventilation exhausted heat recovering unit) | 1.6 [m/s] / 27 - 53degC (depends on required heating performance) |

Required heating performance was set to maintain 25 deg C of the cabin temperature for each ambient condition. The result of the heating performance and COP are shown in Figure5 and Figure 6. In comparing heat pump system A (Outside Air Heat Source) and heat pump system B (ventilation exhausted heat source), both systems have equivalent heating performances, but heat pump system A has a slightly higher COP than heat pump system B. The reason for this is that heat pump system A is able to absorb the outside heat efficiently due to high volume air flow at the front end of the vehicle. Also, in this simulation, the influence of frost formation of the outside evaporator in lower ambient temperature is not taken into consideration. Lastly, an electric air heater is applied to heat pump system A at the -10deg C condition to match the heating performance of heat pump system B.

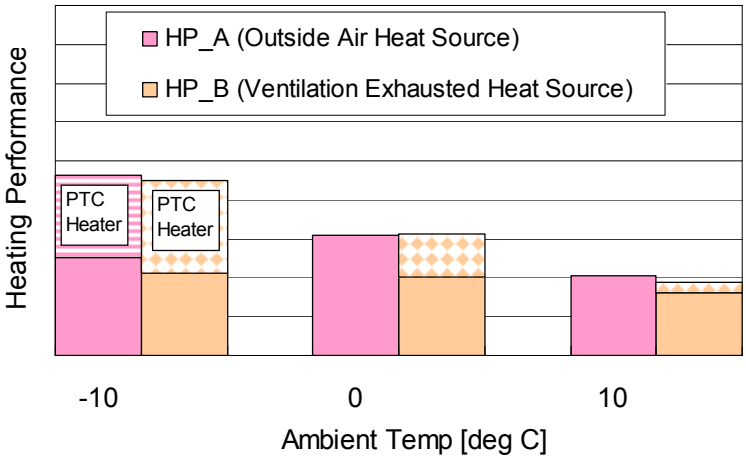



**Figure 5: Simulation Result of Hating Performance**

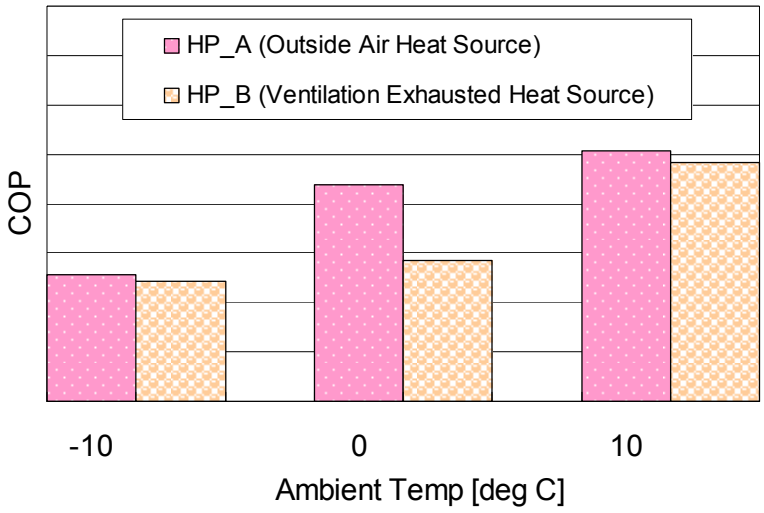



**Figure 6: Simulation Result of COP**

### 3.3.3 Comparison of Heat Pump Systems

Table 4 shows the summary of both heat pump systems. As shown the table 4, both System A and B need to rely on the air PTC heater to have enough heating performance at -10 deg C condition. Also, system A is considered to be the most cost-effective alternative to the current heating system due to simpler refrigerant circuit.

**Table 4: Heat Pump Systems**

| | | | Heat Pump System A | Heat Pump System B |
|---|---|---|---|---|
| **Medium** | | | **Refrigerant/R134a** | **Refrigerant/R134a** |
| **Heating Method** | | | **Heat Pump + Electric Heater** | **Heat Pump + Electric Heater** |
| **Heat Source for Heat Pump** | | | **Outside Air** | **Ventilation Air in Cabin** |
| **Heating Performance** | **Outside air: -10degC** | **Capacity** |  |  |
| | | **COP** |  |  |
| | **Outside air: 10degC** | **Capacity** |  |  |
| | | **COP** |  |  |
| **Cost** | | |  |  |

### 3.4 Vehicle Performance

The vehicle testing has been conducted using prototype sample parts to confirm the heat pump system performance. The test conditions are same as the ones in Table 3. Also, Figure 7 shows the comparison of the power consumption between the electric heater and heat pump systems when the cabin is heated to a comfortable temperature (25deg C).

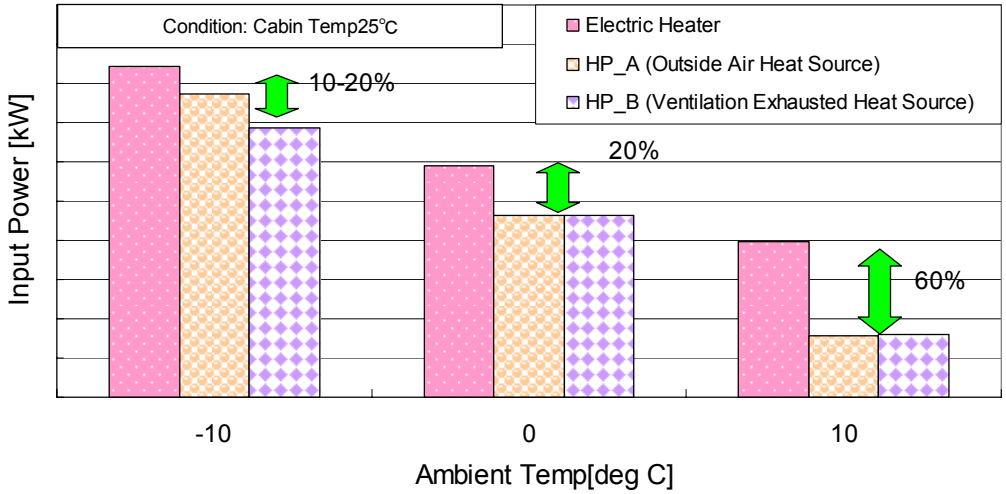



**Figure 7: Comparison of Power Consumption**

Based on the test results shown in Figure 7, it was confirmed that the power consumption of the heat pump system is reduced by 10% to 60% in comparison to the electric heater system. With an ambient temperature of -10 and 0 deg C, since simulation result showed that System A (Outside air heat source) has better COP than System B (Ventilation exhaust heat source), it was expected that the input of System A would be less than that of System B. However, the vehicle test result showed the input power of heat pump system A increased more than heat pump system B. It is considered that the outside evaporator stayed at low ambient environment during the heat pump was operated, and then the refrigerant low side pressure dropped significantly. Once the low side pressure dropped, the surface temperature of the outside evaporator decreased. As a result, frost formation occurred on the outside evaporator surface. In addition to the influence of the frost formation, an electric air heater was applied to heat pump system A at the -10deg C condition to match the heating performance of heat pump system B. Therefore, the input of System A at -10 deg C condition increased more than heat pump system B.

## 4 Summary and Future Prospects

In conclusion, it was confirmed that the power consumption of the heat pump system is reduced by 10% to 60% in comparison to the current electric heater system for eco-friendly vehicles whose market is expected to expand in the future. Also, the application of a heat pump system to these vehicles enables the achievement of a good balance between reducing the parts cost and improving the driving range when heating is in use. In order to accelerate the development of the heat pump system into production for the near future, the following must be completed.

- Establishment of a simulation tool to measure effects of frost formation
- Development of a more efficient energy saving system
- Reliability validation of heat pump system including oil circulation for use year round
- Component validation for parts such as the compressor and electric valves
- Cost reduction by applying production design parts