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# RESEARCHES ON HEAT PUMP SYSTEM USING ROTARY COMPRESSOR IN ELECTRIC VEHICLE

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## ABSTRACT

In China, electric vehicles (EVs) are becoming increasing popular. With several years practical operation experiences, a lot of news reports reveal the existing electrical supplementary heating can dramatically impact the driving range of EVs under cold weather in north China. The high efficient electric heat pump (HP) system has become the research hotspot, but previous researches show the heat pump operation could supply adequate heating capacity only in mild weather conditions when the working fluid is R134a. Since the user can't change environment temperature, choosing a high pressure working fluid to have better heating performance become a realistic choice. Now the aluminum scroll compressor is wildly used in EVs, but because of the material and structure, it can't endure the long term high pressure operation. This paper adopts the low cost steel rotary compressor and high pressure working fluid to build the EV HP system. The heat pump cycles using R134a, R407c, and R290 have been theoretically analyzed. Simulation results show, compared to R134a, using R290 the heating capacity can dramatically improve 51.3% and COP can improve 3.7%. Using R407c, the heating capacity also can increase 46.1%. The 24 cc R134a rotary compressor EV HP system and 21 cc R407c rotary compressor EV HP system has been built, the experiment results the heating capacity of R407c increased by 21.6~31.3%, and the COP of R407c increased by 34.3~37.5% under different conditions. The 21 cc R407c system under -10℃ambient temperature can have heat capacity of 2.59 kW and COP of 1.88 at 6000 RPM.

**Key word:** electric vehicles; heat pump; rotary compressor; refrigerants; heating capacity

## 1. INTRODUCTION

In China, electric vehicles (EVs) are becoming increasing popular. With several years practical operation experiences, a lot of news reports reveal the existing electrical supplementary heating can dramatically impact the driving range of EVs under cold weather (Hosoz & Direk, 2006)(Suzuki & Ishii, 1996).The high efficient electric heat pump system has become the research hotspot, but previous research show the heat pump operation could supply adequate heating capacity only in mild weather conditions when the working fluid is R134a.( Hosoz & Direk, 2006)(Kim, Kim, & Kim, 2012)(Meyer, Yang, & Papoulis, 2004)(Antonijevic & Heckt, 2004). Hosoz and Direk's experimental data revealed that HP operation could provide sufficient amounts of heat to the indoor air stream at mild weather conditions, however, the heating capacity would drop at more severe conditions due to both decreasing evaporating temperatures and activation of the capacity control system. Since the temperature environment can't be changed, choose a high pressure working fluid to have better heating performance become a realistic choice.

Although the new refrigerants such as R1234yf and $CO_2$ are under consideration by the automotive industry. However, R1234yf has the similar thermodynamic and transportation properties to R134a(Seybold, Hill, & Robin, 2011)(Lee, Cho, Park, & Cho, 2012). To alternative R134a, more work should be done. For $CO_2$ using as working fluid, although it shows a good performanceunder the low temperature, otherwise it has a higher requirment for components which makes the cost very high. Besides, other potential working fluid are also studied. As the alternative refrigerant, R290 has a relatively higher capacity and COP than that of R134a especially under low temperature (Ghodbane, 1999)(Chang & Kim, 2000). For those hydrocarbon refrigerants, the EV's system could get the similar capacity and COP to $CO_2$ with no big extra cost at least for now.

Electric compressor is one of the key components in EV's control system. Due to the material and structure of the aluminum scroll compressor which is wildly used in EVs, it can't endure the long term high pressure operation. However, Because of commercial consideration, detailed experimental data and characteristics barely be supplied. Performances of electric compressors only have been studied in entire mobile HP system(Akabane, et al., 1989)(Ikeda, Yoshii, & Tamura, 1990). These studies do not supply detailed experimental data and characteristics.

In order to optimize the system performance at low temperature, lots of studies have been done to improve the compressor , using double-stage compressor or the compressor with enhanced vapor injection replace the usual one.(Dutta, Yanagisawa, & Fukuta, 2001). Though both can solve the problem under low temperature, these approach make the system more complex, harder to control and the cost greatly increased.

In this paper, the project requirements was to maintain 20 ℃ EV compartment temperature under -10 ℃ ambient temperature with no big changes to the existing system. In order to optimize the capacity and COP under low temperature, the system was built by rotary compressor with low cost and high pressure resistance, and adopt the refrigerant has better heating performance. R407c has been successfully used in china electrical bus heat pump system, and the R290 has successfully application in stationary and commercial heat pump system. In this research, the refrigerants R134a, R407c, R290 have been theoretically analyzed; the rotary compressor has been redesign to respectively apply the R134a, R407c, R290; the heat pump test rig has been build; three combinations (compressor, oil, working fluid) under the same cold weather conditions have been experimentally researched.

## 2. HEAT PUMP THERMODYNAMIC CYCLE ANALYSIS

Heat pump system in EV is a vapor compression cycle driven by electric motor. The heat pump heating mode thermodynamic cycle(Fig 1) was simplified based on some assumptions as the following:

- The rotary compressor had a constant displacement (21 cc).
- The compressor efficiencies changed with motor speed (provided by compressor manufacture).
- The throttle process in expansion valve was isenthalpic.
- The superheat at outdoor heat exchanger outlet and subcooling at indoor heat exchanger outlet were 5 K.
- The pressure drops in heat exchangers and tubes were ignored.
- The evaporation temperature was constant (-20 ℃) for -10 ℃ ambient air temperature conditions and the condensation temperature was constant (40 ℃) for 20 ℃ vehicle compartment temperature.

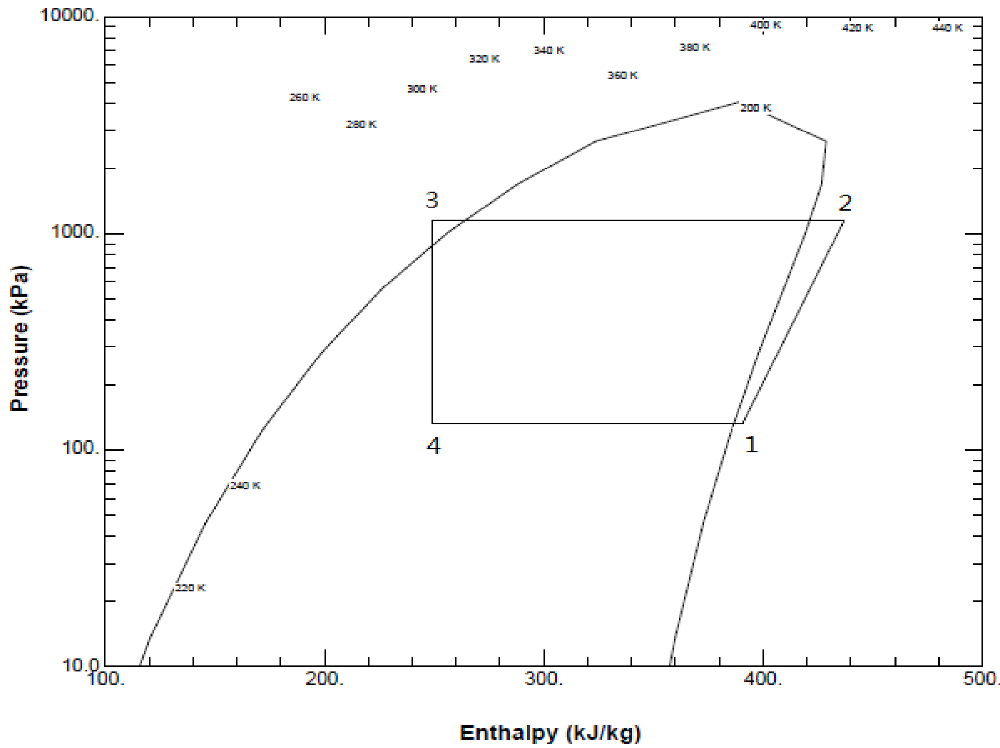


**Fig 1:** R134a EV HP heating mode basic thermodynamic cycle in logP-h diagram

The heating capacity, compressor consumption power, system COP and refrigerant mass flow rate were calculated by Eqs. (1)-(4):

$$Q_{heat} = \dot{m}(h_1 - h_4) \tag{1}$$

$$W_{comp} = \dot{m} * (h_2 - h_1)/\eta_{isen} \tag{2}$$

$$\mathrm{COP} = \frac{Q_{heat}}{W_{comp}} \tag{3}$$

$$\dot{m} = \frac{RPM}{60} * Disp_{comp} * \rho_1 * \eta_{vol} \tag{4}$$

All the above equations and calculations were carried out using Engineering Equation Solver (EES, F-Chart Software, 2014). The thermodynamic properties of R134a, R290 and R407c were from REFPROP 9.1 developed by NIST (US National Institute of Standards and Technology). The ambient and compartment temperature, compressor motor speed, and compressor efficiencies (provided by manufacture) were shown in Table 1.

**Table 1:**EV HP operation conditions

| | | | | |
|---|---|---|---|---|
| **Ambient air temperature** | -10 ℃ | | | |
| **EV compartment temperature** | 20 ℃ | | | |
| **Compressor speed** | 3000 | 4000 | 5000 | 6000 |
| **Volume efficiency** | 0.868 | 0.877 | 0.866 | 0.867 |
| **Isentropic efficiency** | 0.850 | 0.800 | 0.750 | 0.700 |

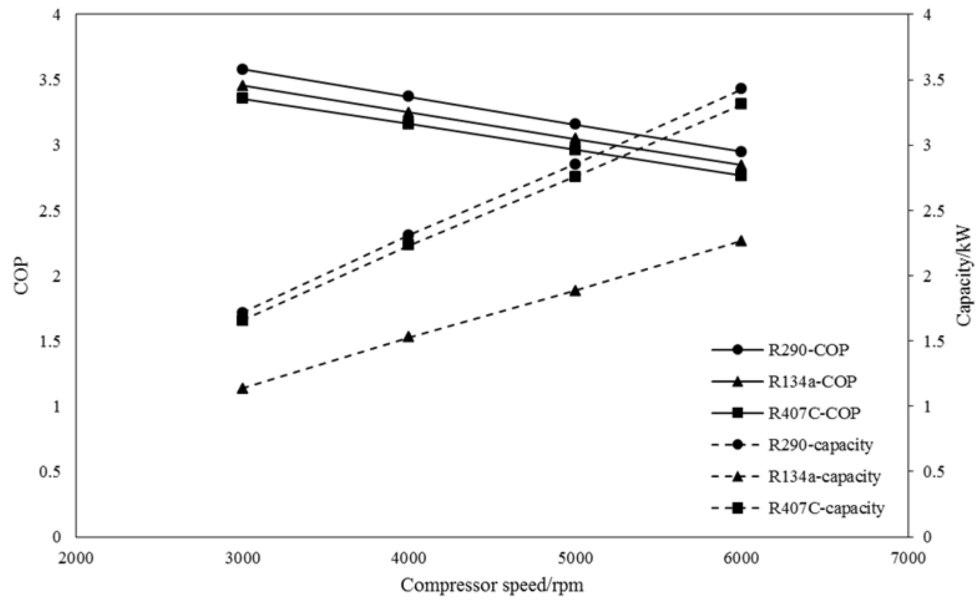


**Fig 2:** Thermodynamic cycle analysis results

The theoretical EV HP system performance comparison of R134a, R290 and R407c was shown in Fig 2. It was implied that R290 has best system COP and heating capacity. Using R134a as benchmark, by adopting R290 the heating capacity can dramatically improve 51.3% and COP also can improve 3.7%. In R407c system, the heating capacity also can increase 46.1%, but the COP would slightly decease 2.8%. The simulation result show R290 has the best performance in three refrigerant, and R407c also can be a good choice to have better heating capacity.

## 3. EXPERIMENTAL RESULT AND ANALYSIS

### 3.1 Experimental Setup

The structure of EVHP system was shown in Figure 3. This system adopted three heat exchangers: outdoor heat exchanger, inner condenser and inner evaporator. The switch between cooling and heating modes was realized by on and off of bypass valve and model air door of HVAC. In cooling mode, the bypass valve near to the inlet/outlet of inner evaporator was closed, while the bypass valve near to the inlet of the outer heat exchanger was open. In the meantime, model air door of HVAC near to condenser was closed. Refrigerants under high temperature and high pressure go through the inner condenser without heat exchange. At this time, the outer heat exchanger and inner evaporator were used as condenser and evaporator of the entire system. In the heat pump mode, the bypass valve near to the inlet/outlet of inner evaporator was open, while the bypass valve close to inlet of the outer heat exchanger was closed. In the meantime, model air door near to inner condenser was open. The inner evaporator and outer heat exchanger were used as condenser and evaporator of the heat pump system. Inner evaporator was bypassed without functioning.

The EVHP system was installed in two chambers. In each chamber, the air temperature and humidity could be maintained at the set value by the environmental control unit which is composed of cooling system, heating system and the PID of humidifier. The rotational speed of the electric compressor is measured by its own controller. The face velocity of air on the outer heat exchanger is controlled by axial flow fan. Pressure sensors, temperature sensors and the mass flow meter were installed to measure parameters in the system. In addition, the experiment also needs to collect the input voltage and current of compressor, dry/wet bulb temperature in environmental chamber, face velocity of outer heat exchanger. Types and precision of each testing parameter are listed in Table 2.

**Table 2:** Precision of testing items in the test rig

| Testing item | Sensor types | Precision |
|---|---|---|
| Temperature | Thermocouple K-type | ±0.5 ℃ |
| Pressure | Piezoresistive pressure sensors | ±10.0 kPa |
| Current | Pliers type multimeter | ±(2%+5) A |
| Voltage | Pliers type multimeter | ±(0.8%+1) V |
| Air speed | Rotary vane anemometer | ±0.05 m/s |

## 3.2 Test conditions

Since the traditional petroleum-fueled vehicle has no heat pump system, heating conditions of automotive heat pump are not available. Considered with domestic and commercial heating conditions of heat pump system, heating conditions of automotive heat pump were made shown in Table 3.

**Table 3:** Heating model conditions

| Conditions | Range |
|---|---|
| Compressor rotational speed | 3000、4000、5000、6000 rpm |
| Temperature of outdoor chamber | -10 ℃ |
| Temperature of indoor chamber | 20 ℃ |
| Outer heat exchanger Face velocity | 6.0 m/s |
| HVAC blower voltage | 6.7, 12.5 VDC |
| Evap. Outlet Superheat | 5~10 ℃ |
| Refrigerant | R134a, R407c |

## 3.3 Results analysis

In the experiments of heating test conditions, the data were recorded and saved after the temperature of the indoor/outdoor chamber and the conditions become stable. The compressor speed is charged by stable direct current. After measuring its electric current I and voltage U, the electric power consumed can be calculated by the following equation:

$$W_{comp} = I * U \tag{5}$$

The enthalpy of air $h_{air}$ can be got by measuring the temperature and look them up in thermal tables. Then we can calculate heat capacity of each heat exchanger.

In heating mode：

$$Q_{heat} = \dot{m}_{air}(h_{air,out} - h_{air,in}) \tag{6}$$

$$\mathrm{COP} = \frac{Q_{heat}}{W_{comp}} \tag{7}$$

According the heating mode conditions in Tab 3, the compressor speed varied from 3000~6000RPM; HVAC blower voltage is 6.7V and 12.5V, corresponding air flow volume rate is 200m$^3$/h and 350m$^3$/h; because R290 compressor is under developing, the refrigerants were only R134a and R407c. Simulation result show poor heating performance of R134a, manufacture provide 24 cc R134a compressor and 21 cc R407c compressor. The followed results analysis was based on these conditions.

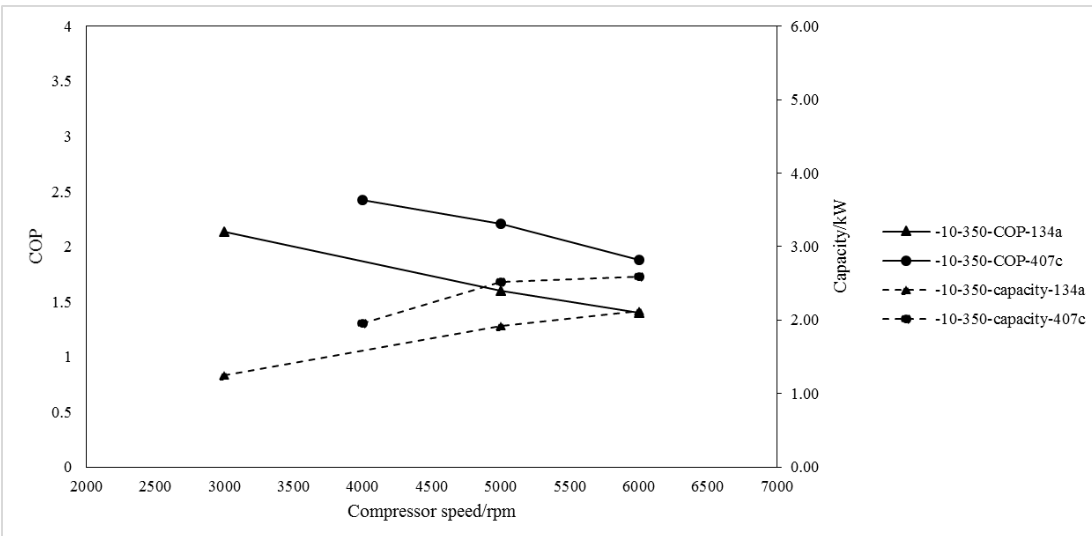


**Fig 3**: Heating mode experimental performance of R134a and R407c

Fig 3 shows the comparison of heating capacity and COP of R134a and R407c, results show 21 cc R407c system has better performance than 24 cc R134a system. Even the compressor displacement is smaller, the heating capacity of R407c increased by 21.6~31.3%, which is in accordance with simulation results. But the COP of R407c also increased by 34.3~37.5%, which is different with simulation results.

Fig 4 shows the comparison of simulation and experiment results of R134a system, because the simulation ignored some losses of cycle, the COP results show a gap between simulation and experiment, the difference of heating capacity is much smaller. But both of the COP and heating capacity have same variation trend in simulation and experiment.

Fig 5 shows the comparison of simulation and experiment results of R407c system, Similar with R134a, both of the COP and heating capacity have same variation trend in simulation and experiment.

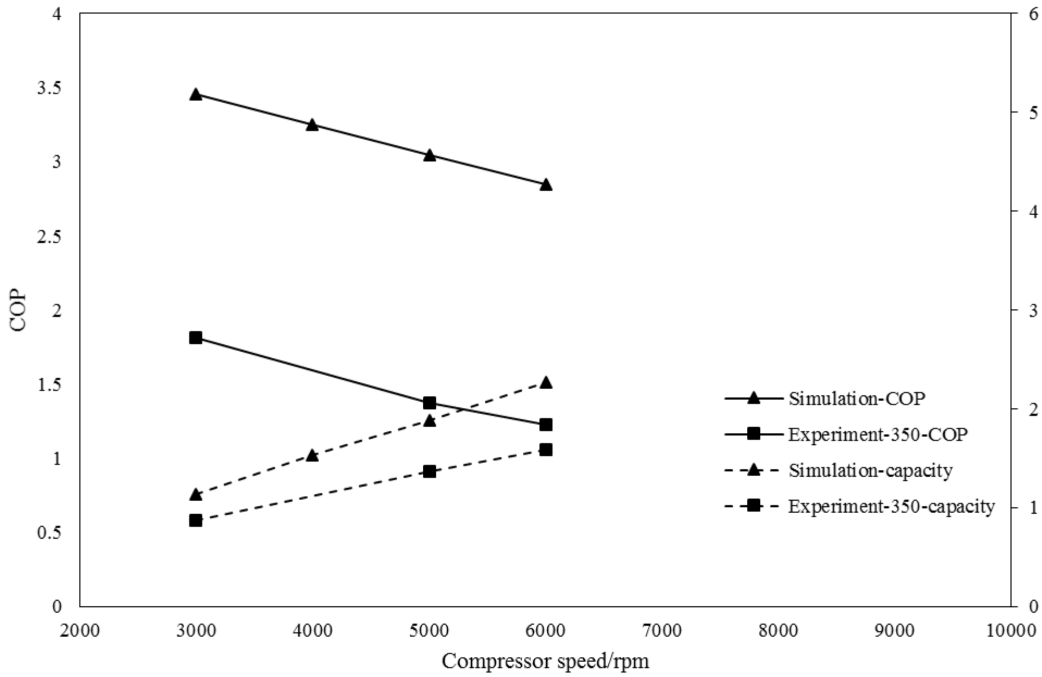


**Fig 4:** Simulation and experiment comparison of R134a system

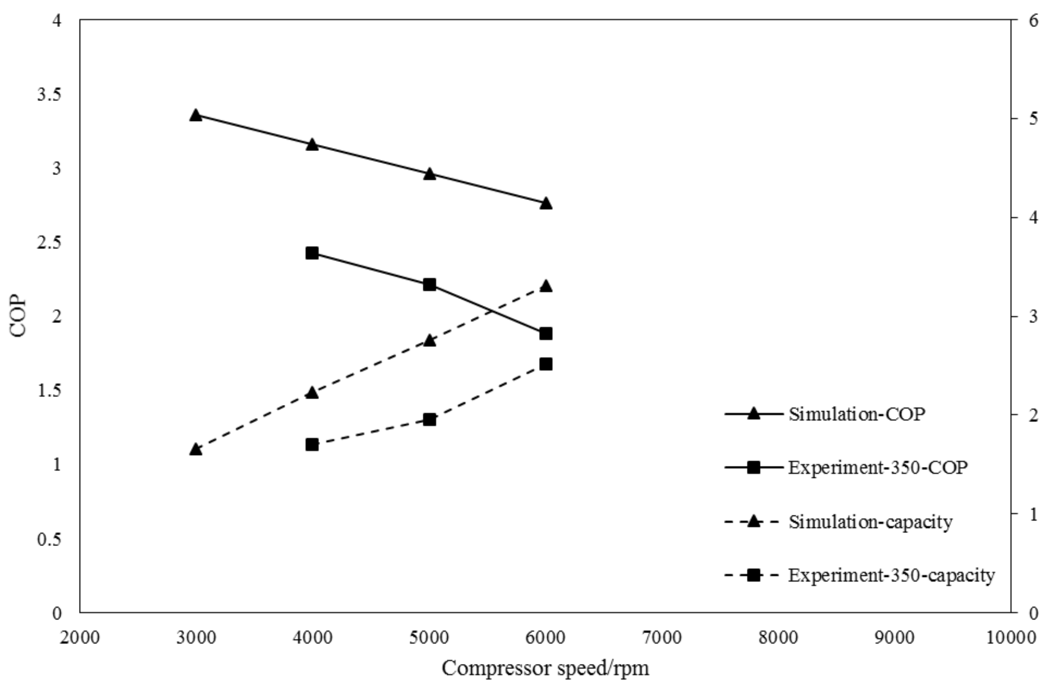


**Fig 5:** Simulation and experiment comparison of R407c system

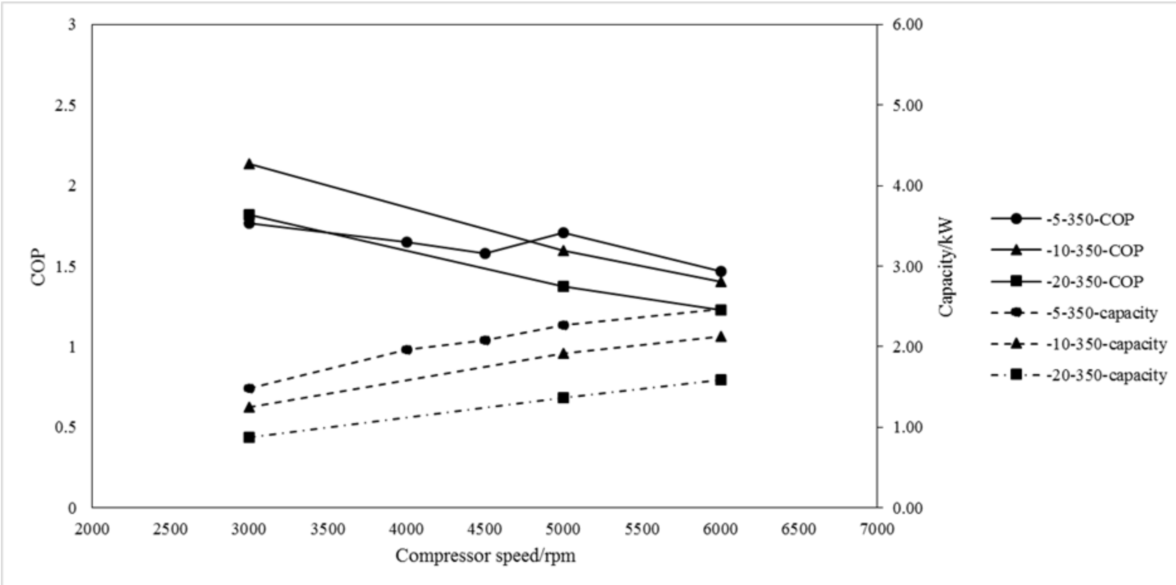


**Fig 6:** Effect of ambient air temperature

Fig 6 shows effect of ambient air temperature in R134a system, results show both of the COP and heating capacity decrease with ambient air temperature, but the COP under -5℃ ambient temperature in 3000, 4000, 4500 RPM didn't show good results as expected. It's worth noting that under -20℃ ambient temperature the R134a rotary compressor system have COP of 1.82 under 3000RPM, and have heating capacity of 1.59kW under 6000RPM, but the COP is only 1.23.

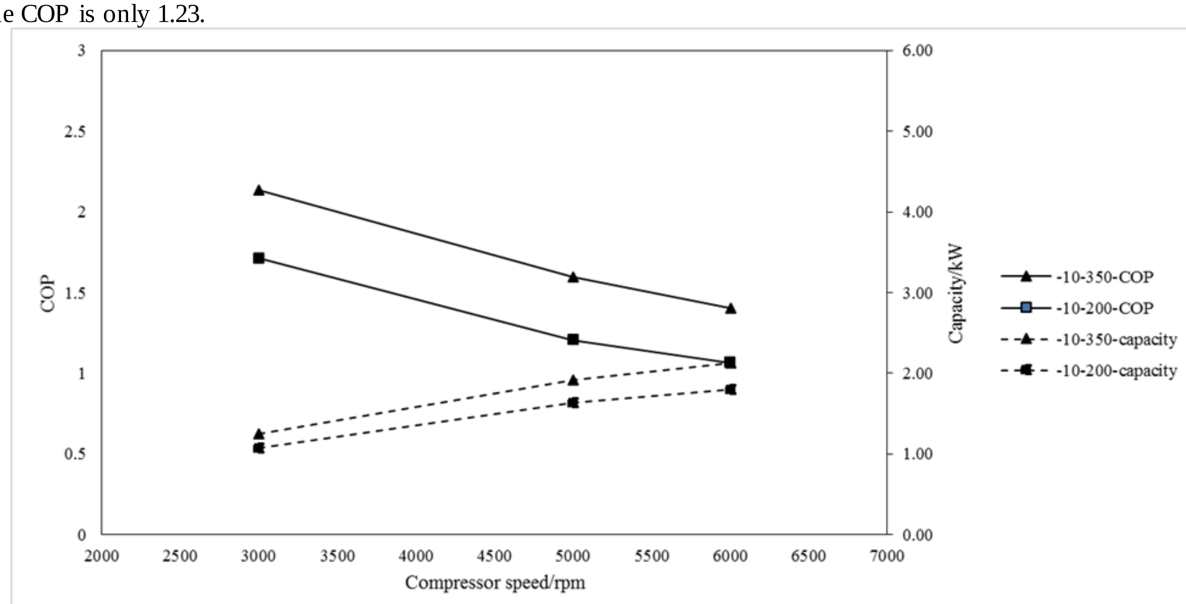


**Fig 7:** Effect of HVAC air flow rate

Fig 7 shows effect of HVAC air flow rate, results show when the air flow rate increased from 200m$^3$/h to 350m$^3$/h , both of the COP and heating capacity increase with air flow rate.

## 4. CONCLUSIONS

In this paper, the refrigerant R134a, R407c, R290 in EV HP systems have been theoretically analyzed. Simulation results show, compared to R134a, the heating capacity of R290 system can dramatically improve 51.3% and COP also can improve 3.7%. Using R407c, the heating capacity also can increase 46.1%, but the COP would slightly decease 2.8%. The 24cc R134a rotary compressor EV HP system and 21cc R407c rotary compressor EV HP system has been built. The experiment results show 21cc R407c system has better performance than 24cc R134a system ,the heating capacity of R407c increased by 21.6~31.3% which matches well with simulation results and the COP of R407c increased by 34.3~37.5% under different conditions. It's worth noting that under extremely -20℃ambient temperature the R134a rotary compressor system operates smoothly.Under 3000RPM, the COP of R134a system is 1.82 while under 6000RPM, the the COP is only 1.23. The 21cc R407c system under -10℃ambient temperature can have heating capacity of 2.59kW and COP of 1.88 at 6000RPM.These results show the potential of the rotary compressor in EV HP system.

## NOMENCLATURE

| | |
|---|---|
| AC | air conditioning |
| COP | coefficient of performance |
| EV | electric vehicle |

## REFERENCES

1. Akabane, H., Ikeda, S., Kikuchi, K., Tamura, Y., Sakano, R., Bessler, W., & Harms, H. (1989). *Evaluation of an electrically driven automotive air conditioning system using a scroll hermetic compressor with a brushless DC motor* (No. 890308). SAE Technical Paper.
2. Antonijevic, D., & Heckt, R. (2004). Heat pump supplemental heating system for motor vehicles. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 218* (10), 1111-1115.
3. Chang, Y. S., Kim, M. S., & Ro, S. T. (2000). Performance and heat transfer characteristics of hydrocarbon refrigerants in a heat pump system. *International journal of refrigeration, 23* (3), 232-242.
4. Dutta A. K., Yanagisawa T., & Fukuta M.(2001). An investigation of the performance of a scroll compressor under liquid refrigerant injection. *International Journal of Refrigeration, 24* (6): 577-587.
5. Dutta, A. K., Yanagisawa, T., & Fukuta, M. (2001). An investigation of the performance of a scroll compressor under liquid refrigerant injection. *International Journal of Refrigeration, 24* (6), 577-587.
6. Ghodbane, M. (1999). An Investigation of R152 and Hydrocarbon Refrigerants in Mobile Air Conditioning. *SAE transactions, 108* (6; PART 1), 1658-1673.
7. Hosoz, M., & Direk, M. (2006). Performance evaluation of an integrated automotive air conditioning and heat pump system. *Energy conversion and management, 47* (5), 545-559.
8. Ikeda, S., Yoshii, Y., & Tamura, Y. (1990). *Air conditioning electric vehicles with an electronically driven variable speed scroll type compressor* (No. 901738). SAE Technical Paper.
9. Jelinski, E., & Olsen, P. C. (1997). *Design, manufacturing and operating experience with an electric vehicle: Cold climate experience* (No. 971626). SAE Technical Paper.
10. Kim, K. Y., Kim, S. C., & Kim, M. S. (2012). Experimental studies on the heating performance of the PTC heater and heat pump combined system in fuel cells and electric vehicles. *International Journal of Automotive Technology, 13* (6), 971-977.
11. Lee, Y., & Jung, D. (2012). A brief performance comparison of R1234yf and R134a in a bench tester for automobile applications. *Applied Thermal Engineering, 35*, 240-242.
12. Meyer, J., Yang, G., & Papoulis, E. (2004). *R134a heat pump for improved passenger comfort* (No. 2004-01-1379). SAE Technical Paper.
13. Seybold, L., Hill, W., & Robin, J. J. (2011). Internal heat exchanger system integration for R1234yf refrigerant. *SAE International Journal of Materials & Manufacturing, 4* (1), 181-194.
14. Suzuki, T., & Ishii, K. (1996). *Air conditioning system for electric vehicle* (No. 960688). SAE Technical Paper.