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Dynamic performance analysis of an R744/R290 cascade heat pump system for electric vehicles

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Abstract

A R744/R290 cascade heat pump system is proposed as an alternative to conventional single-stage systems using synthetic refrigerants. A dynamic simulation model based on finite-volume discretization was developed to analyze system behavior in heating mode under varying operating conditions. The effects of R744 refrigerant charge and compressor speed on system performance were investigated, and the results were compared with those of a single-stage R744 heat pump at the same heating capacity. The proposed cascade system exhibited a significantly higher coefficient of performance (COP), demonstrating its effectiveness in improving heating efficiency. The results confirm the feasibility of the R744/R290 cascade heat pump as a promising heating solution for electric vehicles (EVs).

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Keywords: Electric Vehicle, Cascade heat pump, Dynamic simulation, Finite volume method, heating capacity

1. Introduction

Electric vehicles (EVs) rely on positive temperature coefficient (PTC) heaters for heating due to insufficient waste heat. As a result, when a 6 kW-class PTC heater operates, the driving range can be reduced by up to 63% at an outdoor temperature of 0 °C, which poses a substantial challenge to achieving the desired range performance [1]. As an alternative, heat pump systems have been adopted for EV heating. Compared to PTC heaters, heat pumps consume less electrical energy, leading to a reported improvement in driving range of approximately 15% at an outdoor temperature of 0 °C [2].

The performance of a heat pump is strongly influenced by both refrigerant selection and operating conditions. While R1234yf is currently used as the standard refrigerant in automotive HVAC systems, it may be classified as a per- and polyfluoroalkyl substance (PFAS) under future regulations [3]. This potential regulatory risk necessitates the consideration of alternative refrigerants that can deliver comparable performance.

In this study, natural refrigerants—propane (R290) and carbon dioxide (R744)—are considered alternative working fluids. Previous studies have reported limitations in heating and cooling performance as well as efficiency when natural refrigerants are applied to a conventional heat pump system, suggesting that alternative system configurations may be required for their effective utilization [3],[4]. To enhance system performance by exploiting the thermodynamic characteristics of each refrigerant, a cascade heat pump system is proposed. Compared to a conventional single-stage heat pump, the cascade configuration operates with lower compression ratios and is particularly advantageous when the temperature difference between the heat source and the heat sink is large [5].

Accordingly, system performance is analyzed in heating mode by varying key operating parameters, including refrigerant charge and compressor speed. Furthermore, a dynamic simulation approach is employed to more realistically represent the transient behavior of an actual EV heat pump system.

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2. Methods

2.1. System description

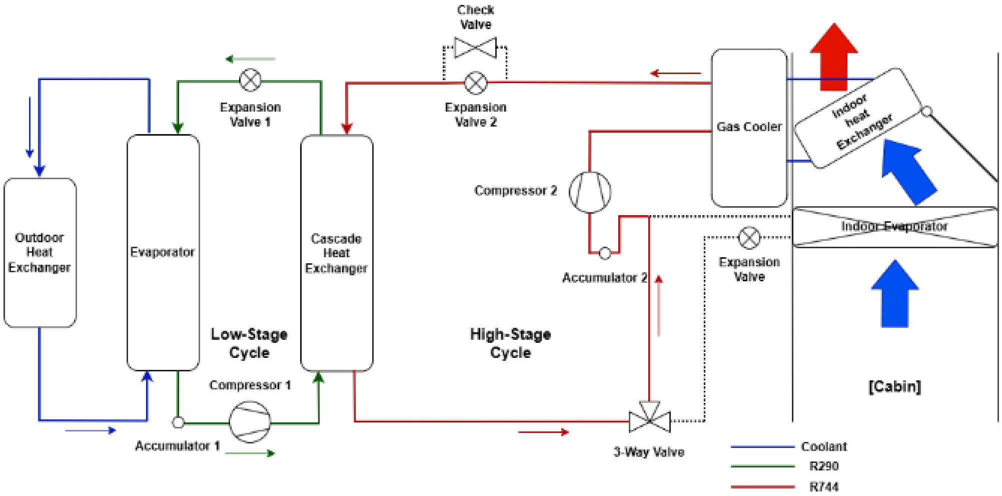


Figure 1. Schematic of a proposed cascade heat pump system

In the proposed cascade heat pump system, as illustrated in Fig. 1, the overall configuration can be divided into two subsystems: the high-stage cycle and the low-stage cycle. R744, a refrigerant with non-toxic and non-flammable properties, is employed in the high-stage cycle. R290 is adopted in the low-stage cycle to ensure safety, given its flammability characteristics. These cycles are thermally coupled through a cascade heat exchanger (CHX). The system employs a water–ethylene glycol (50%) mixture as an intermediate coolant to facilitate heat transfer with air by utilizing Louvered fin–tube heat exchangers (LFTHX), such as the outdoor heat exchanger (ODHX) and the indoor heat exchanger (IDHX), while all other components employ plate heat exchangers (PHX). The detailed specifications of the heat exchangers are summarized in Table 1.

Table 1. Geometrical characteristics of the heat exchangers in the proposed cascade heat pump system

Type	Parameter	Component		
		Gas cooler	CHX	Evaporator
Plate heat exchanger (S316L)	Plate width [mm]	285	285	285
	Plate length [mm]	105	105	105
	Plate thickness [mm]	0.3864	0.3864	0.3864
	Total number of plates	33	33	27
	Total channel volume [m^3]	0.0018	0.0018	0.0014
			IDHX	ODHX
Louvered fin-tube (Aluminum)	Core width [mm]		256	572.6
	Core height [mm]		215	365
	Core depth [mm]		45	20
	Total volume [m^3]		6.1e-04	3.7e-04
	Fin pitch [mm]		1.8	1.3
	Louver angle [°]		33	30

2.2. Model description

The mathematical modeling employed for the simulation is based on the formulation proposed by MacArthur et al. [6]

2.2.1. Mathematical modeling of heat exchangers

The governing equations consist of the conservation of mass, momentum, and energy, and the following assumptions are made, as shown below:

- Only the heat exchangers are treated as transient, while the compressor, expansion valve, and accumulator are assumed to operate under quasi–steady-state.
- The refrigerant state at the initial condition is two-phase in both cycles.
- The governing equations are solved in one dimension along the flow direction.
- Axial conduction, pressure variations, and viscous dissipation are neglected.
- Since pressure waves propagate at the speed of sound, which is significantly faster than the system time step (1 s), pressure drop is neglected in this model.

The finite volume method (FVM) was employed. In this method, the heat exchanger is discretized along the flow direction into a series of identical control volumes. The heat transfer rate is calculated using the enthalpy obtained for each control volume at the specified pressure. The heat-transfer correlations used are listed in Table 2.

Table 2. The heat transfer correlations used in each heat exchanger

Author(s)	Equation	Conditions
Yan and Lin [7]	$Nu = 0.2121Re^{0.78}Pr^{1/3}$	PHX, single-phase
	$Nu = 1.926{Pr_l}^{1/3}Bo^{0.3}{Re_{eqv}}^{0.5}[(1-x)+x\left(\frac{\rho_l}{\rho_g}\right)]$	PHX, evaporating
Shah [8]	$h = h_l[(1-x)^{0.8} + \frac{3.8x^{0.76}(1-x)^{0.04}}{(^{P}/_{P_{crit}})}$	PHX, condensing
Chang and Wang [9]	$j = Re^{-0.49}(\frac{\theta}{90})^{0.27}(\frac{F_p}{L_p})^{-0.14}(\frac{F_l}{L_p})^{-0.29}(\frac{T_d}{L_p})^{-0.23}(\frac{L_l}{L_p})^{0.68}(\frac{T_p}{L_p})^{-0.28}(\frac{\delta_f}{L_p})^{-0.05}$	LFTHX, air heat exchange
Gnielinski [10]	$Nu = 0.0499RePr\frac{D_h}{L} + 7.547 \ (Re < 1400)$	LFTHX, coolant heat exchange
	$Nu = 0.012(Re^{0.87}-280)Pr^{0.4}[1+(\frac{D_h}{L})^{2/3}] \ (Re \geq 1400)$	LFTHX, coolant heat exchange

2.2.2. Compressor

The compressor operates under a polytropic process with an exponent (n) of 1.1779 to determine the outlet density. The volumetric efficiency (η_V) and isentropic efficiency (η_s) are set to 0.75 and 0.7, respectively.

$$\rho_{out} = (\frac{P_{out}}{P_{in}})^{1/n}\rho_{in} \tag{1}$$

2.2.3. Electronic Expansion Valve (EEV)

The EEV controls the degree of superheat (DSH) of the heat pump system by adjusting the valve opening. In this study, a PI controller is employed, and the target DSH is set to 5 °C. To maintain the target DSH, the valve area is continuously adjusted over time, thereby regulating the refrigerant mass flow rate.

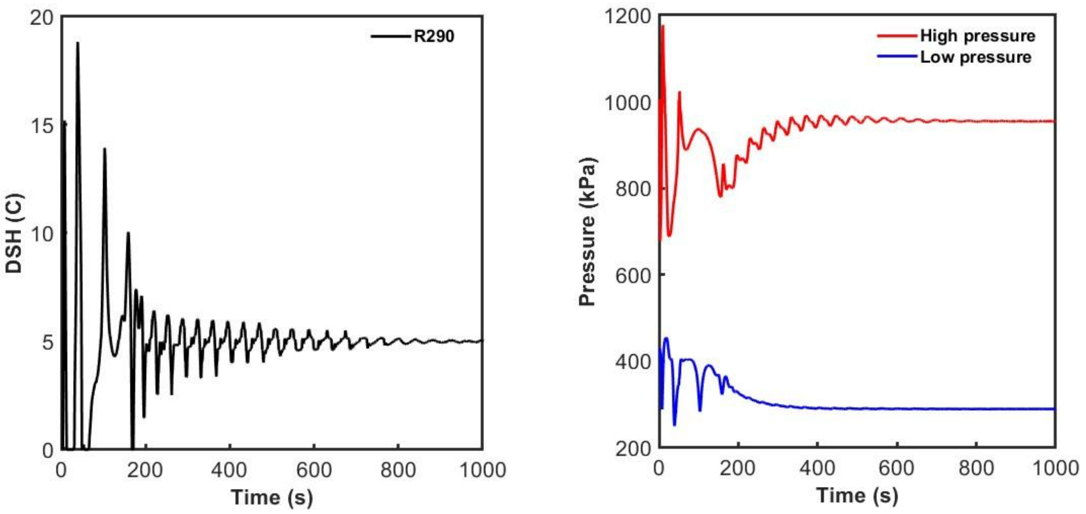


Figure 2. The dynamic characteristics of low-stage cycle (R290)

Fig. 2 illustrates the dynamic behavior of the low-stage cycle during the simulation. The DSH converges to the target value as the control system stabilizes, while both the high- and low-side pressures gradually settle into steady-state values.

Accordingly, once the system exhibits steady-state behavior, the performance trends under different operating parameters are evaluated using time-averaged values obtained over the interval of 500–1000 s.

3. Results and Discussion

The two operating conditions considered in this study are summarized in Table 3.

Table 3. Experimental study conditions

Test conditions	R744 refrigerant charge [kg]	R744 compressor speed [RPM]	R290 refrigerant charge [kg]	R290 compressor speed [RPM]	Temperature [℃]	
					Outdoor	Indoor
Case 1	0.7, 0.8, 0.9, 1.0, 1.1	200	0.15	4000	0	25
Case 2	0.9	200, 300, 400, 500, 600	0.15	4000	0	25

To assess the feasibility of the proposed cascade heat pump system, its performance was compared with that of a conventional heat pump. The comparison was conducted at the same R744 refrigerant charge of 0.8 kg and under the same indoor and outdoor air conditions, while maintaining a heating capacity of 1.22 kW. The proposed cascade system achieved a COP of 2.5446, whereas the conventional heat pump system exhibited a COP of 1.3489, indicating the superior performance of the proposed configuration.

3.1. Effects of R744 refrigerant charge on system performance

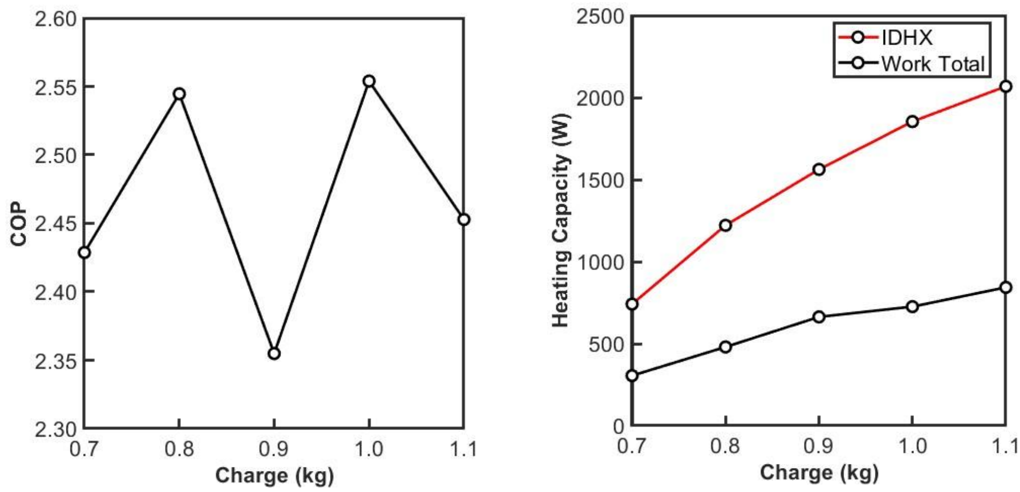


Figure 3. The effects of R744 refrigerant charge on COP for Case 1

Fig. 3 shows the variation in COP with respect to the R744 refrigerant charge. The COP, defined as the ratio of heating capacity to compressor work, exhibits an overall increasing trend as the refrigerant charge increases, accompanied by increases in both. However, the rate of increase differs between these two quantities. Fig. 4 presents the P–h diagrams of both cycles in the cascade heat pump system. While the pressure trends at the cascade heat exchanger are similar for the high-stage and low-stage cycles, the magnitude of pressure variation is larger in the high-stage cycle. In addition, the gas cooler pressure increases progressively with increasing refrigerant charge. In this study, the heat transfer rate in each heat exchanger was calculated as the product of the overall heat transfer coefficient, heat transfer area, and the temperature difference. Fig. 5 illustrates the heating capacity expressed in terms of these two parameters. As the refrigerant charge increases, the maximum UA value exhibits an overall decreasing trend. The temperature difference between the R744 refrigerant and the coolant in the gas cooler beyond a charge of 1.0 kg, the reduction in temperature difference becomes more pronounced toward the outlet region of the gas cooler.

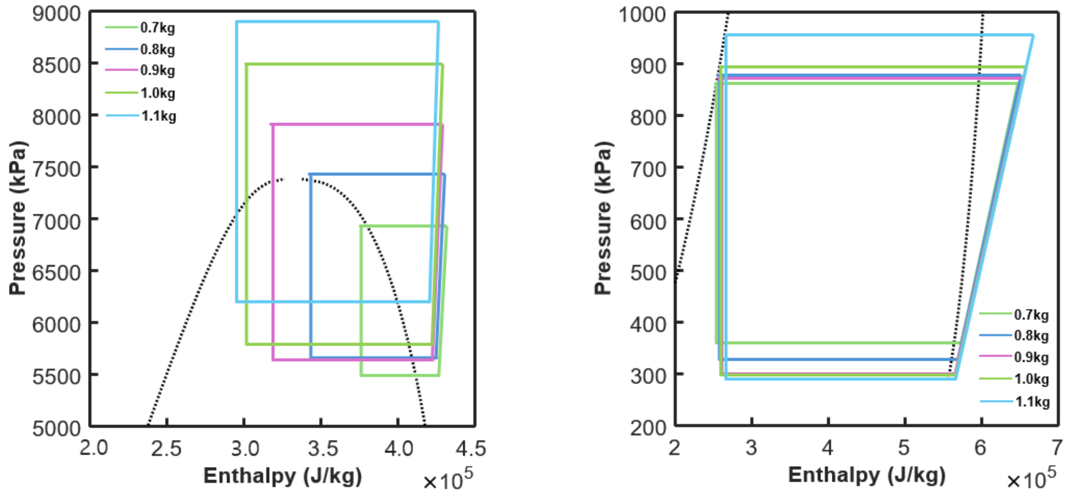


Figure 4. The P-h diagrams for Case 1 (left: High-stage, right: Low-stage)

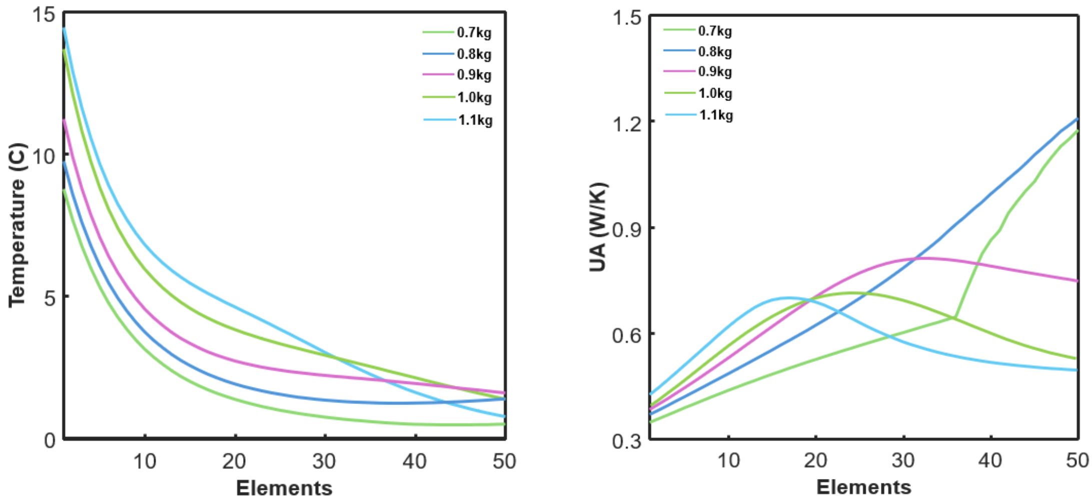
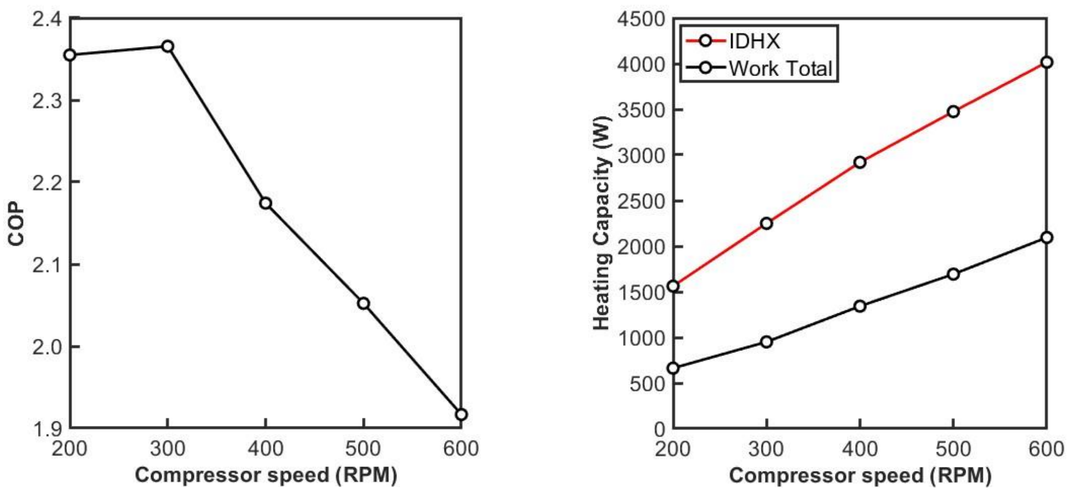


Figure 5. The tendency of the temperature difference and UA for the high-stage cycle

3.2. Effects of R744 compressor speed on system performance



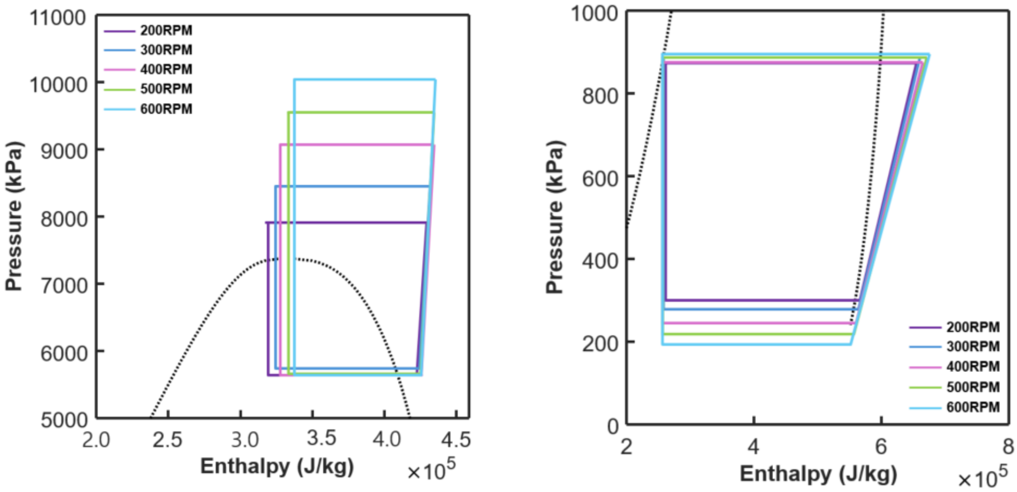


Figure 6. The effects of R290 compressor speed on COP for Case 2

In Case 2, an increase in compressor speed resulted in an increase in the gas cooler pressure of the high-stage cycle and a decrease in the evaporating pressure of the low-stage cycle, exhibiting a trend similar to that observed in a single heat pump system. This pressure variation leads to an increased temperature difference between the indoor and outdoor sides, thereby promoting enhanced heat transfer.

4. Conclusion

This study investigated the heating performance of an R744/R290 cascade heat pump system for EV using a dynamic simulation approach. The results confirmed that optimal COP values exist depending on refrigerant charge and compressor speed, and that the proposed cascade system achieves a significantly higher COP than a conventional single-stage heat pump under identical heating capacity.

Acknowledgements

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