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Thermal Parameters Optimization of the R744/R134a Cascade Refrigeration Cycle Using Taguchi and ANOVA Methods

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Abstract: In recent years, the use of R744 natural refrigerant has become increasingly popular in a wide range of applications from air conditioning to low-temperature refrigeration. This study focuses on optimizing the thermodynamic parameters of the R744/R134a cascade cycle operating under evaporative temperature varying from −23 °C to −29 °C, operating in tropical climates region. The parameters include the evaporating temperature, the condensing temperature, the subcooling temperature, and the superheating temperature in the low temperature cycle, and the evaporating temperature, the subcooling temperature, and the superheating temperature in the high temperature cycle. The study has given a rating of the influence of thermodynamic parameters on the coefficient of performance (COP) of the system. In addition, the study shows that the optimal dataset for all the above thermodynamic parameters is $A_3B_3C_2D_1E_1F_3$ with a COP of 2.560 in theory and 2.461 in experiment. Moreover, the ANOVA analysis method for the variances also shows the consistency of the above results with the highest error of 3.54% compared to the experiment.

Keywords: optimization; cascade refrigeration system; Taguchi and ANOVA methods

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1. Introduction

The problems of climate change and the negative impacts of industrial production activities over the past several years have made the research on emissions reduction more urgent than ever. In particular, the refrigeration industry plays a key role in producing emissions that destroy the ozone layer. Traditional refrigerants can cause global warming and destroy the ozone layer and are gradually being studied in comparison to more environmentally friendly ones. Carbon Dioxide (CO_2) or R744 refrigerant is a natural refrigerant that can be easily produced. It is considered a potential substitute for traditional refrigerants and is completely environmentally friendly because it has Ozone Depletion Potential (ODP = 0) and the ability to cause the effect of Global Warming Potential (GWP) is also negligible (GWP = 1). The application of R744 in air conditioning systems in recent years has led to many positive results, but the experimental studies of R744 in low-temperature cycles, especially in cascade refrigeration systems, are quite limited.

Regarding cascade refrigeration systems using R744, there is quite a lot of design research, applicability evaluation, and cycle performance evaluation by comparison with different configurations of refrigeration systems and different refrigerants. San-Kock et al. [1] experimentally evaluated a cascade refrigeration system of R134a/R744 refrigerant designed for commercial refrigeration systems with low evaporation temperatures from −40 °C to −30 °C. However, the optimization results were not mentioned in this study.

Getu and Bansal [2] analyzed the thermodynamic parameters of the cascade refrigeration system using R744/R717 to optimize the design and operation parameters of the system. The design parameters considered include superheating, subcooling, evaporation temperature, and condensation temperature. A multilinear regression was used to propose the expressions for maximum COP. Dubey et al. [3,4] analyzed the thermodynamic parameters of the R744/C_3H_6 transcritical cascade system using EES software (version v10.561). This study proposed the optimal performance parameters such as Topt, COP_{max}, and a prediction of mass flow rate of C_3H_6 and R744. Lee et al. [5] analyzed the thermodynamic parameters of a cascade refrigeration system using the R744/R717 to determine the optimum condensing temperature of a cascade head exchanger with different design parameters. The studies related to a couple of refrigerants R717/R744 [6–10] focused on the effect of some operating parameters including condensation temperature, evaporation temperature, and temperature difference in the condenser in the cascade heat exchanger. Related to the systems using R744/R404A [11–14], the studies focused on optimizing the COP with the internal heat exchanger. In addition, Song et al. [15] compared the performance of combination systems using R134a/R744 and cascade systems for heating applications under specific operating conditions. Wang et al. [16] performed an experimental process to analyze the cooling performance of a cascade refrigeration system using the R717/R744 affected by operating parameters such as evaporation temperature and condensation temperature in the low temperature cycle, superheat, and temperature difference in the cascade heat exchanger. Queiroz et al. [17] studied and evaluated the performance of a cascade refrigeration system using R744/R134a as an alternative to conventional small systems that typically use R404A or R22 refrigerant. Dopazo and Fernández-Seara [18] conducted the research, design, and fabrication of a cascade refrigeration system using R717/R744 with a cooling capacity of 9 kW and an evaporation temperature of −50 °C. Bhattacharyya et al. [19] investigated the R744/C3H8 cascade system for simultaneous cooling and heating. Some studies [20,21] researched a cascade refrigeration system using a pair of R744/R717 where the devices are both an evaporator and a firming condensing device used as a cascade heat exchanger. Bhattacharyya et al. [22] investigated a N_2O/R744 cascade system used for simultaneous refrigeration and heating applications. Yari and Mahmoudi [23] studied the cascading R744/R744 cycles with a transcritical R744 cycle per the subcritical R744 cycle and compared them to a two-stage cycle. Cabello et al. [24] compared the energy performance of a cascade refrigeration system working with R134a/R744 compared to R290/R744, R1270/R744, R600a/R744, and R1234ze/R744 to find proper refrigerant pairs which are effective and environmentally friendly. Zhao et al. [25] investigated the theoretical simulation and thermodynamic analyses of the Linde–Hampson refrigeration system to compare the optimal COP. Ojeda et al. [26] analyzed an experimental of the energy and environmental performance of low-GWP refrigerants R513A, R1234yf, and R436A as alternatives for R134a in a cascade refrigeration system. Ye et al. [27] presented multi-objective optimizations of an ultra-low temperature cascade refrigeration system using response surface methodology and desirability approach. Jara et al. [28] proposed two modifications of the cascade system C_2H_4/C_4H_{10} by including an ejector device to improve the COP. Furthermore, some studies related to substitute refrigerants in high temperature cycle [29–31] analyzed and compared the operating parameters to optimize the COP of the system including R134a, R717, R1234yf, R600, R1234ze, and R290. Most research [10–31] focused on analyzing and optimizing the performance of these systems using different refrigerant pairs. Researchers typically concentrate on analyzing thermodynamic parameters such as the coefficient of performance, compressor discharge temperature, and the temperature difference in heat exchangers. To achieve maximum efficiency, several software were employed to calculate and predict system performance and compare it with

other traditional systems. The main objective is to optimize the design and operation of cascade refrigeration systems by adjusting parameters such as evaporating temperature, condensation temperature, and temperature difference in heat exchangers. Additionally, studies also investigate the environmental impact and energy-saving potential of cascade refrigeration systems, continuously seeking methods to optimize performance through research in theory and experimentation.

Regarding the use of optimization algorithms in recent years for refrigeration cycles, the use of R744 is quite limited. Canbolat et al. [32] established thermodynamic modeling of the absorption refrigeration system cycle and the variability of COP and eCOP calculated for different working conditions with different parameter ranges. Some studies [33–35] evaluated the vapor compression cascade cooling cycle with R744, R404A, R407C, R717, R410A, R513A, R32, and R290 by considering statistical analysis methods and Taguchi and ANOVA methods to optimize performance to achieve optimal operating conditions to achieve maximum COP and exergy efficiency. COP and exergy efficiency within the operating parameters range in the assessment of 3.274% and 37.63%, respectively. Recent research [29–32] in optimizing the performance and exergy efficiency of refrigeration cycles has heavily relied on statistical analysis techniques such as Taguchi and ANOVA in theory, but they have not been verified and compared experimentally.

From the literature above, the studies have focused on the design and operation of cascade refrigeration systems by adjusting key parameters such as evaporating temperature, condensation temperature, and temperature differences in heat exchangers. Moreover, research on optimizing cascade refrigeration systems is essential because it helps determine the optimal operating conditions for refrigeration systems, thereby improving efficiency and energy savings. The optimization efforts (identifying the impact of parameters such as evaporating temperature, condensing temperature, subcooling, and superheating in the low temperature cycle, and evaporating temperature, subcooling, and superheating in the high temperature cycle both in theory and experiment) represent a new research direction, particularly in regions with tropical climates. This research has the potential to significantly contribute to reducing environmental impacts and enhancing the economic efficiency of refrigeration systems in the future, especially in countries located in tropical climate regions.

2. Experimental Methods

This research will be conducted in two steps: theoretical calculations and experimental setup. The theoretical calculation is applied based on statistical theory (robust design) and combines the calculation of cascade refrigeration systems and data analysis. The experimental system will then be set up and the experiments will be based on calculations as well as initial theoretical parameters accompanied by data acquisition. The results will be compared and evaluated.

2.1. System Parameters and Design

The cascade refrigeration system in this study operates based on coupling two refrigeration cycles using R134a (GWP = 1430) for the high temperature cycle (HTC) and R744 (GWP = 1) for the low temperature cycle (LTC). The evaporator of the high temperature cycle is used to cool the low-stage condenser at a welded plate heat exchanger which is called a cascade heat exchanger. The cascade heat exchanger serves as an evaporator of the high temperature cycle and a condenser of the low temperature cycle. The p-h diagram for this prototype is shown in Figure 1.

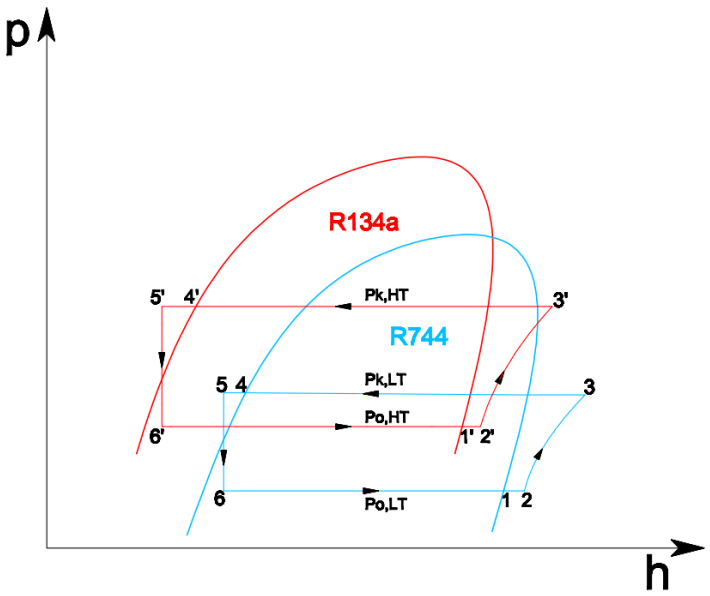


Figure 1. The p-h diagram of the cascade vapor compression refrigeration cycle.

For calculating and designing the cascade refrigeration system, we will calculate each cycle separately and calculate the same as the single-stage refrigeration cycle. The condition for stable operation of the system is that the cooling capacity of HTC is equal to the condensing capacity of LTC while the heat loss is ignored.

In this study, the key components of a testing cycle were designed based on the computational theory [36] of the following equations:

The cooling capacity was calculated as follows:

$$Q_{EVA} = m_{R744}(h_1 - h_6) \quad (1)$$

The COP of the cascade system based on adiabatic compression work:

$$COP = Q_{EVA}/(W_{COM1} + W_{COM2}) \quad (2)$$

Energy balance equations for LTC compressor:

$$W_{COMP1} + m_{R744}h_2 = m_{R744}h_3 \quad (3)$$

Energy balance equations for the cascade heat exchanger:

$$m_{R744}h_3 + m_{R134a}h_{6'} = m_{R134a}h_{2'} + m_{R744}h_5 \quad (4)$$

Energy balance equations for HTC compressor:

$$W_{COMP2} + m_{R134a}h_{2'} = m_{R134a}h_{3'} \quad (5)$$

where Q_{EVA} is cooling capacity at LTC (kW); h is enthalpy of fluid at state points (kJ/kg); COP is coefficient of performance; W is adiabatic compression energy (kW); and m is mass flow rate of fluid (kg/s).

Based on the theory of calculating and designing a cascade refrigeration system as well as experimental conditions in this study, it can be shown that the factors that directly affect the system's COP are superheat temperature, subcooling temperature, condensing temperature, and evaporating temperature at the low temperature cycle, and evaporating

temperature and subcooling temperature at the high temperature cycle, respectively. For the overall system, the initial design parameters and their values are shown in Table 1.

Table 1. The initial design data and their values.

Parameters	Value
Cooling capacity	1000 W
The condensing temperature at the high temperature cycle	38 °C
The evaporating temperature at the high temperature cycle	2 °C
The cascade temperature difference	4 °C
The evaporating temperature at the low temperature cycle	−25 °C
The superheating at the high temperature cycle	8 °C
The superheating at the low temperature cycle	7 °C
The subcooling at the high temperature cycle	8 °C
The subcooling at the low temperature cycle	7 °C
The mass flow rate of the high temperature cycle	27.7 kg·h^{-1}
The mass flow rate of the low temperature cycle	15.8 kg·h^{-1}

2.2. Design of Experiments for Taguchi and ANOVA Analysis

Based on the thermodynamic parameters designed in Table 1 and the theoretical framework referenced in [34], this study considers typical operating conditions of tropical climates. Accordingly, it identifies the key factors and their respective levels that influence the optimization of the coefficient of performance (COP). The corresponding data are presented in Table 2. The outside temperature is a noise factor, and it depends on the time that data receive in a day. It ranges from 30 °C to 32 °C, so the condensing temperature of HTC created three results of the COP (COP cases for trial$_1$, trial$_2$, and trial$_3$ are calculated in the morning, evening, and afternoon in a day, respectively). The factors and the level are mentioned in Table 2.

Table 2. System parameters and values levels.

Parameters Factors	Levels		
	1	**2**	**3**
A: Superheating temperature of low temperature cycle (°C)	5	6	7
B: Evaporating temperature of high temperature cycle (°C)	1	3	5
C: Subcooling temperature of low temperature cycle (°C)	2	3	4
D: Subcooling temperature of high temperature cycle (°C)	4	5	6
E: Condensing temperature of low temperature cycle (°C)	6	7	8
F: Evaporating temperature of low temperature cycle (°C)	−29	−26	−23

Robust designs in general and Taguchi in particular are approaches to product design to produce products of excellent quality and reliability. In this study, the Taguchi method is used for the purpose of calculating the input parameters of the system to provide data for the system COP.

The Taguchi method classifies the product characteristics into three categories, based on the signal to noise ratio relationship. The three categories that comprise the models for evaluation include Larger is better, Smaller is better, Normal is better. For a refrigeration system, the assessment of the completeness of the cycle is expressed through the COP, the higher COP is better. Therefore, in this study, the signal to noise ratio value will be taken to be as Large as possible with the following equations:

The Larger is better (maximize) value is calculated by

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (6)$$

The total DOF can be described by the following:

$$\mathrm{DOF} = \sum_{i=1}^{i=n_{Lf}} (L_{f,i} - 1) + \mathrm{DOF}_{error} \quad (7)$$

ANOVA analysis is based on the parameters with the following equations, Adjusted Mean Square (MS) Regression and Adjusted Mean Square Error (MSE), which are described by the following:

$$\text{MS Regression} = \frac{\text{SS Regression}}{\text{DOF Regression}} = \frac{\sum(\hat{y}_i - \overline{y})^2}{n_{Lf}(L_f - 1)} \quad (8)$$

The Larger is better (maximize) value is calculated by the following:

$$\mathrm{MSE} = \frac{\mathrm{SS}_{error}}{\mathrm{DOF}_{error}} = \frac{\sum(\hat{y}_i - \overline{y})^2}{\mathrm{DOF} - \text{DOF Regression}} \quad (9)$$

The F-value is determined by the following equation:

$$F = \frac{\text{Adj MS Term}}{\mathrm{MSE}} \quad (10)$$

To set the orthogonal matrix level for the system based on the selected parameters and their levels, several orthogonal matrix tables have been considered to ensure accuracy and reliability during theoretical and experimental analysis. However, the L27 table is suitable in this case to balance the factors of cost and time for entire operating parameters of the system with high reliability. Table 3 shows the detailed data in the L27 orthogonal table.

Table 3. L27 orthogonal table for the Taguchi method and its interpretation.

	Factors						L27					
No.	**A**	**B**	**C**	**D**	**E**	**F**	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**
1	5	1	2	4	6	−29	1	1	1	1	1	1
2	5	1	2	4	7	−26	1	1	1	1	2	2
3	5	1	2	4	8	−23	1	1	1	1	3	3
4	5	3	3	5	6	−29	1	2	2	2	1	1
5	5	3	3	5	7	−26	1	2	2	2	2	2
6	5	3	3	5	8	−23	1	2	2	2	3	3
7	5	5	4	6	6	−29	1	3	3	3	1	1
8	5	5	4	6	7	−26	1	3	3	3	2	2
9	5	5	4	6	8	−23	1	3	3	3	3	3
10	6	1	3	6	6	−26	2	1	2	3	1	2
11	6	1	3	6	7	−23	2	1	2	3	2	3
12	6	1	3	6	8	−29	2	1	2	3	3	1
13	6	3	4	4	6	−26	2	2	3	1	1	2
14	6	3	4	4	7	−23	2	2	3	1	2	3
15	6	3	4	4	8	−29	2	2	3	1	3	1
16	6	5	2	5	6	−26	2	3	1	2	1	2
17	6	5	2	5	7	−23	2	3	1	2	2	3
18	6	5	2	5	8	−29	2	3	1	2	3	1
19	7	1	4	5	6	−23	3	1	3	2	1	3
20	7	1	4	5	7	−29	3	1	3	2	2	1
21	7	1	4	5	8	−26	3	1	3	2	3	2
22	7	3	2	6	6	−23	3	2	1	3	1	3
23	7	3	2	6	7	−29	3	2	1	3	2	1
24	7	3	2	6	8	−26	3	2	1	3	3	2
25	7	5	3	4	6	−23	3	3	2	1	1	3
26	7	5	3	4	7	−29	3	3	2	1	2	1
27	7	5	3	4	8	−26	3	3	2	1	3	2

2.3. Experimental Setup

The experimental system is a cascade refrigeration system including the following: The high temperature cycle uses R134a, and the low temperature cycle uses R744. The two cycles are connected via a micro plate heat exchanger. The system is operated to obtain thermodynamic points of the cycle through the temperature sensors and the pressure sensors of the system. In addition, both cycles are equipped with mass flow rate meters with high accuracy; data are recorded in real time every 10 min via the MX100 data acquisition. Therefore, it is easy to determine the cooling capacity, adiabatic compression work, and the COP of the cycle. Details of the arrangement of experimental equipment and their accuracy are shown in Figure 2 and Table 4. A real photo of the testing system is shown in Figure 3. Details about the basic specifications, manufacturers, and models of the main components in the experimental system are presented in Table 5.

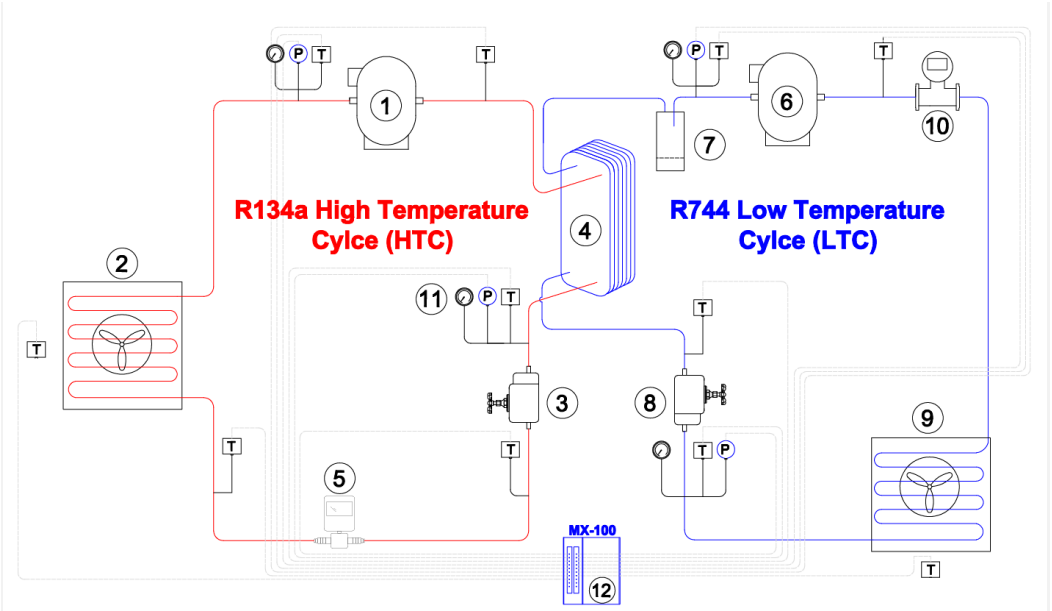


Figure 2. The schematic view of the cascade vapor compression refrigeration cycle.

Table 4. Measuring devices and their accuracies.

Device	Accuracy	Range	Manufacturer
Thermocouples—T type	±0.1 °C	−270–400 °C	Omega (Michigan City, IN, USA)
Clamp meter	±2%FS	0–600 A	Hioki (Nagano, Japan)
Digital acquisition	-	20 channels	Yokogawa (Tokyo, Japan)
Pressure sensor	±0.5%FS	0–100 bars	Sensys (Gyeonggi-do, Republic of Korea)
Turbine flow rate meter	±0.5%	400 to 5000 L/h	Digital Flow Co., Ltd. (Chungcheongbuk-do, Republic of Korea)
Thermal mass flow gas meter	±1.5%	0.5 to 28 Nm^3/h	Anhui Jujie (Anhui, China)

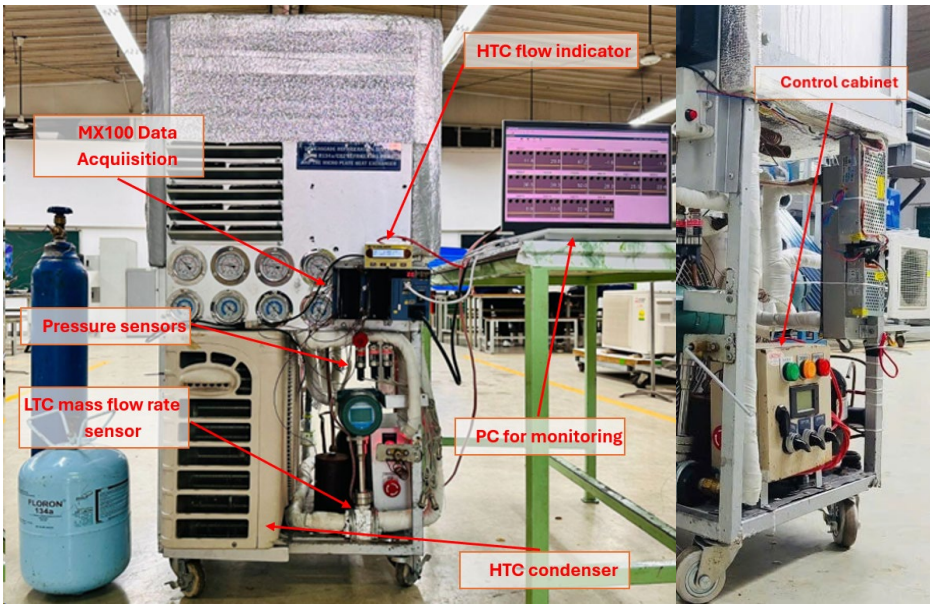


Figure 3. Real experimental system.

Table 5. Details of the main components and manufacturers.

Components	Specifications	Manufacturer
LTC Compressor	Hermetic Compressor	Sanden (Shandong, China) Model SRcACA; No. 6456
HTC Compressor	Hermetic Compressor	Kulthorn (Bangkok, Thailand); Model AE2428ZK-SR
HTC Condenser	Finned Tube Heat Exchanger	Samsung (Chonburi, Thailand); Model AR10MVFHGWKXSVHeat Transfer Area: 2.8 m^2
Cascade Heat Exchanger	Welded Plate Heat Exchanger	Danfoss (Nordborg, Denmark) Model D22/16; No. 021H1297

3. Results and Discussion

This study will initially compare the use of the Taguchi method and the ANOVA variance analysis method using theoretical calculations on EES version v10.561 software, thereby suggesting which factors affect the COP of the system. The authors used the Stat function in Minitab software v22.2.2 to select optimization using the Taguchi method to determine the rank of elements and analyzed the variance using the General Linear Model function to give an F-value and *p*-value based on a given level of meaning. Next, the experimental data are used to verify the evaluations made on the theory. The cold room is guaranteed to be well insulated; the cooling load reaches the room temperature of −18 °C to meet the evaporating temperature requirements of −23 °C, −26 °C, −29 °C at steady-state. For the optimal dataset, a team will continue to run the test many times in various weather conditions to make a conclusion.

3.1. Taguchi and ANOVA Theory Calculation Results

Theoretical COP results according to the Taguchi method are shown in Table 6. After performing the analysis and evaluation according to the Taguchi method, the results as shown in Table 7 and Figure 4. It is noted that the factors (A–F) are from Tables 2 and 3.

Table 6. Theoretical COP results according to the Taguchi method.

Case	A	B	C	D	E	F	COP_{trial1}	COP_{trial2}	COP_{trial3}	COP_{mean}
1	5	1	2	4	6	−29	2.153	2.138	2.074	2.122
2	5	1	2	4	7	−26	2.254	2.133	2.114	2.167
3	5	1	2	4	8	−23	2.360	2.284	2.259	2.301
4	5	3	3	5	6	−29	2.259	2.241	2.174	2.225
5	5	3	3	5	7	−26	2.368	2.244	2.222	2.278
6	5	3	3	5	8	−23	2.485	2.354	2.276	2.372
7	5	5	4	6	6	−29	2.368	2.247	2.228	2.281
8	5	5	4	6	7	−26	2.487	2.459	2.384	2.443
9	5	5	4	6	8	−23	2.613	2.479	2.447	2.513
10	6	1	3	6	6	−26	2.343	2.269	2.148	2.253
11	6	1	3	6	7	−23	2.456	2.326	2.299	2.36
12	6	1	3	6	8	−29	2.079	2.019	2.011	2.036
13	6	3	4	4	6	−26	2.431	2.303	2.227	2.32
14	6	3	4	4	7	−23	2.551	2.516	2.384	2.484
15	6	3	4	4	8	−29	2.154	2.09	2.079	2.108
16	6	5	2	5	6	−26	2.469	2.34	2.314	2.374
17	6	5	2	5	7	−23	2.594	2.558	2.474	2.542
18	6	5	2	5	8	−29	2.178	2.164	2.052	2.131
19	7	1	4	5	6	−23	2.520	2.385	2.304	2.403
20	7	1	4	5	7	−29	2.133	2.07	2.059	2.087
21	7	1	4	5	8	−26	2.233	2.214	2.148	2.198
22	7	3	2	6	6	−23	2.565	2.429	2.347	2.447
23	7	3	2	6	7	−29	2.159	2.096	2.034	2.096
24	7	3	2	6	8	−26	2.262	2.143	2.076	2.16
25	7	5	3	4	6	−23	2.667	2.526	2.488	2.560
26	7	5	3	4	7	−29	2.239	2.221	2.156	2.205
27	7	5	3	4	8	−26	2.347	2.274	2.204	2.275

Table 7. Response table for signal to noise ratio.

No	A	B	C	D	E	F
1	7.224	6.892	7.063	7.150	7.341	6.618
2	7.174	7.131	7.163	7.182	7.198	7.131
3	7.102	7.476	7.274	7.168	6.960	7.751
Delta	0.122	0.584	0.211	0.031	0.381	1.134
Rank	5	2	4	6	3	1

Based on the results in Table 7 and Figure 4, it indicates the influence on the COP of each factor in the cascade refrigeration system. Classifying in order of rank from 1 to 6 and corresponding to the above rank, we can see that the evaporation temperature factor is the factor that most affects the COP. Accordingly, the impact order of parameters affecting COP is $T_{e_R744} > T_{e_R134a} > T_{c_R744} > T_{sc_R744} > T_{sh_R744} > T_{sc_R134a}$. The parameters corresponding to the Taguchi method are F > B > E > C > A > D. According to the values of Table 6, the most optimal set of factors for the system is A_3 B_3 C_2 D_1 E_1 F_3. Applying this set of factors can give the most optimal COP value from Taguchi's analysis. The operating condition of the system is as follows: T_{sh_R134a} = 7 °C; T_{e_R134a} = 5 °C; T_{sc_R744} = 3 °C; T_{sc_R134a} = 4 °C; T_{c_R744} = 6 °C; and T_{e_R744} = −23 °C. The highest COP obtained corresponding to the above set of factors is 2.560.

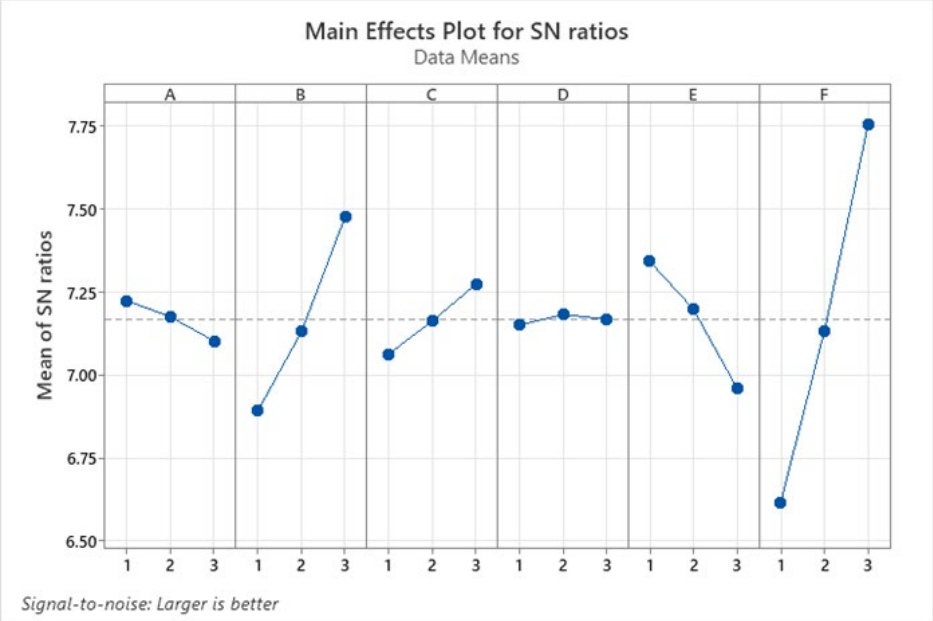


Figure 4. Influence according to SN value.

Continuing to use the Minitab software v22.2.2 and analyzing using the ANOVA method, the data obtained are shown in Tables 8 and 9.

Table 8. Analysis of variance in the ANOVA table for COP.

Source	DF	Adj SS	Adj MS	F-Value	*p*-Value
Regression	6	0.572522	0.095420	127.39	0.000
A	1	0.004000	0.004000	5.34	0.032
B	1	0.108474	0.108474	144.82	0.000
C	1	0.013704	0.013704	18.30	0.000
D	1	0.000133	0.000133	0.18	0.678
E	1	0.044104	0.044104	58.88	0.000
F	1	0.402105	0.402105	536.82	0.000
Error	20	0.014981	0.000749		
Total	26	0.587503			

Table 9. Variance components from ANOVA analysis.

Source	Var	% of Total	SE Var	Z-Value	*p*-Value
A	0.000158	0.49%	0.000231	0.682521	0.247
B	0.006032	18.65%	0.006104	0.988209	0.162
C	0.000692	2.14%	0.000764	0.905338	0.183
D	0.000000	0.00%	*	*	*
E	0.002441	7.54%	0.002513	0.971328	0.166
F	0.022382	69.18%	0.022454	0.996797	0.159
Error	0.000647	2.00%	0.000229	2.828427	0.002
Total	0.032351				
		2 Log likelihood = −79.307472			

Note: * is the symbol for a value not considered because it has a near zero impact.

According to the ANOVA variance analysis for the COP in Table 8, the larger the value of F, the higher the influence of that factor on the COP. Based on the ANOVA analysis table, the F-value of the evaporation temperature at LTC factor is the highest (536.82) and the lowest is the F-value of the HTC subcooling temperature factor is the lowest (0.18). From

the ANOVA variance analysis table, the COP based on the given factors will change the total calculated value, and it can predict the change in the COP based on the above factors.

In addition, the rate of impact on the COP are shown in Table 9. We can see that the largest influencing parameter is the LTC evaporation temperature with an impact percentage of 69.18%. This is followed by the HTC evaporation temperature with an impact percentage of 18.65%, the LTC condensation temperature of 7.54%, the LTC supercooling temperature of 2.14%, the LTC superheat temperature of 0.49%, and the insignificant HTC supercooling temperature. It is concluded that the LTC evaporation temperature has a significant effect on the COP while that the HTC subcooling temperature has less affect to the COP. The factors affecting the COP value are based on the F-value as follows, F > B > E > C > A > D, and this order similarity to the results of Taguchi's analysis is shown in Table 7.

3.2. Taguchi and ANOVA Calculation Results in Experiment

Based on the operating parameters mentioned in the Taguchi L27 table, 27 cases were evaluated on the system, as shown in Figure 3. Conducting experiments and fixing the operating parameters were performed by adjusting the hand throttle valve in both cycles, refilling, or reducing the amount of refrigerant. This control is to adjust the mass flow rate in accordance with the evaporation and condensation temperature to reach the state point parameter closest to the theoretical cycle. The COP is obtained and calculated based on the adiabatic compression at two compressors at LTC and HTC. The cooling capacity is collected at LTC. The condensation temperature at HTC is considered a noise factor, and each experiment will be conducted at three different times during a day. A typical thermodynamic state points statistics for Case 1 in experimental operation are shown in Table 10. COP_{mean} represents the average value mentioned in Table 11.

Table 10. Thermodynamic state points for Case 1.

Thermodynamic State Point	Temperature (°C)	Pressure (bar)
1	−29	14.68
2	−24	14.68
3	51.2	40.62
4	5.9	40.61
5	3.4	40.61
6	−29	14.70
1′	0.76	3.02
2′	9.9	3.02
3′	49.3	8.81
4′	34.7	8.79
5′	30.6	8.79
6′	1.1	3.03

Applying the ANOVA variance analysis method to the experiment, the same results are also obtained in Table 12 and Figure 5, after running the analysis based on the Taguchi method. It indicates the F-value of the evaporation temperature at HTC factor is the highest (218.80) and the lowest is the F-value of the HTC subcooling temperature factor is the lowest (0.07).

From the ANOVA analysis method, the rate of impact on the COP was determined. According to the results in Table 13, it indicates that the largest influencing parameter is the LTC evaporation temperature with an impact percentage of 69.18%. The LTC subcooling temperature factor and the LTC superheating temperature factor have less effects on the COP of the system. We can conclude that the order of the factors affecting the based COP

and the F-value is as follows, F > B > E > D > C > A, and these orders are consistent with the results of the Taguchi analysis in Table 10. However, this arrangement is slightly different from the theoretical analysis. It can be observed that the percentage contribution in Table 14 was determined according to the ANOVA analysis method. The three factors D, C, and A have almost similar contribution percentages, so there is an order change between the above three factors with the least impact on COP 0% for factors A and C and 0.41% for the corresponding D factor. The change in the rank level of the factors of the subcooling and superheating temperatures is derived from the major influence of the ambient temperature and the error of the measuring device during the experiment.

Table 11. Experimental COP results according to the Taguchi method.

Case	A	B	C	D	E	F	COP_{mean}
1	5	1	2	4	6	−29	2.012
2	5	1	2	4	7	−26	2.008
3	5	1	2	4	8	−23	2.208
4	5	3	3	5	6	−29	2.060
5	5	3	3	5	7	−26	2.161
6	5	3	3	5	8	−23	2.269
7	5	5	4	6	6	−29	2.108
8	5	5	4	6	7	−26	2.22
9	5	5	4	6	8	−23	2.293
10	6	1	3	6	6	−26	2.038
11	6	1	3	6	7	−23	2.185
12	6	1	3	6	8	−29	1.904
13	6	3	4	4	6	−26	2.181
14	6	3	4	4	7	−23	2.341
15	6	3	4	4	8	−29	1.975
16	6	5	2	5	6	−26	2.306
17	6	5	2	5	7	−23	2.327
18	6	5	2	5	8	−29	1.979
19	7	1	4	5	6	−23	2.308
20	7	1	4	5	7	−29	1.961
21	7	1	4	5	8	−26	1.971
22	7	3	2	6	6	−23	2.400
23	7	3	2	6	7	−29	1.957
24	7	3	2	6	8	−26	2.035
25	7	5	3	4	6	−23	2.461
26	7	5	3	4	7	−29	2.065
27	7	5	3	4	8	−26	2.233

Table 12. Response table for signal to noise ratios from Taguchi method based on experimental data.

Larger Is Better						
Level	**A**	**B**	**C**	**D**	**E**	**F**
1	6.634	6.287	6.551	6.687	6.859	6.007
2	6.554	6.641	6.639	6.604	6.574	6.548
3	6.635	6.895	6.633	6.532	6.389	7.268
Delta	0.081	0.608	0.088	0.155	0.470	1.261
Rank	6	2	5	4	3	1

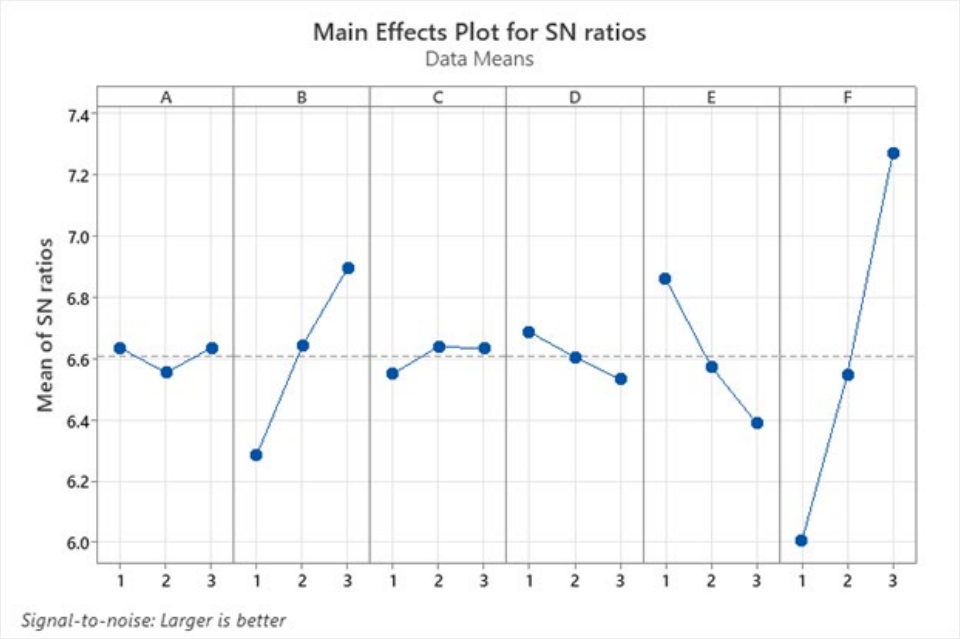


Figure 5. Influence according to SN value diagram.

Table 13. Analysis of variance by ANOVA method based on experiment.

Source	DF	Adj SS	Adj MS	F-Value	*p*-Value
Regression	6	0.610443	0.101741	50.71	0.000
A	1	0.000150	0.000150	0.07	0.787
B	1	0.102303	0.102303	50.99	0.000
C	1	0.001531	0.001531	0.76	0.393
D	1	0.006574	0.006574	3.28	0.085
E	1	0.060900	0.060900	30.35	0.000
F	1	0.438984	0.438984	218.80	0.000
Error	20	0.040127	0.002006		
Total	26	0.650571			

Table 14. Contribution of variance based on ANOVA analysis with experiment data.

Source	Var	% of Total	SE Var	Z-Value	*p*-Value
A	0.000000	0.00%	*	*	*
B	0.005508	15.62%	0.005730	0.961380	0.168
C	0.000000	0.00%	*	*	*
D	0.000145	0.41%	0.000373	0.388319	0.349
E	0.003227	9.15%	0.003449	0.935750	0.175
F	0.024392	69.18%	0.024613	0.991024	0.161
Error	0.001987	5.64%	0.000662	3.000000	0.001
Total	0.035260				

Note: * is the symbol for a value not considered because it has a near zero impact of variance.

3.3. Predicting COP Using Linear Regression

The actual and theoretical results indicate that the common point of both Rank 1 results is the LTC evaporation temperature. This factor has greatly affected the COP change in the cascade refrigeration system.

From Figure 6, the theoretical results and the experimental results are almost similar. The case with the highest COP results achieved in the L25 experiment in the Taguchi table was 2.56 in theory and 2.461 in the experiment, respectively. According to the results from the two ANOVA analyses of theory and experiment, both make a percentage contribution

to the COP, and both methods give the percentage of LTC evaporation temperature as the highest at 69.18% and have the greatest influence. Moreover, it shows that the HTC subcooling temperature and the HTC superheating temperatures have a disproportionate percentage of contribution so there is less impact on the COP.

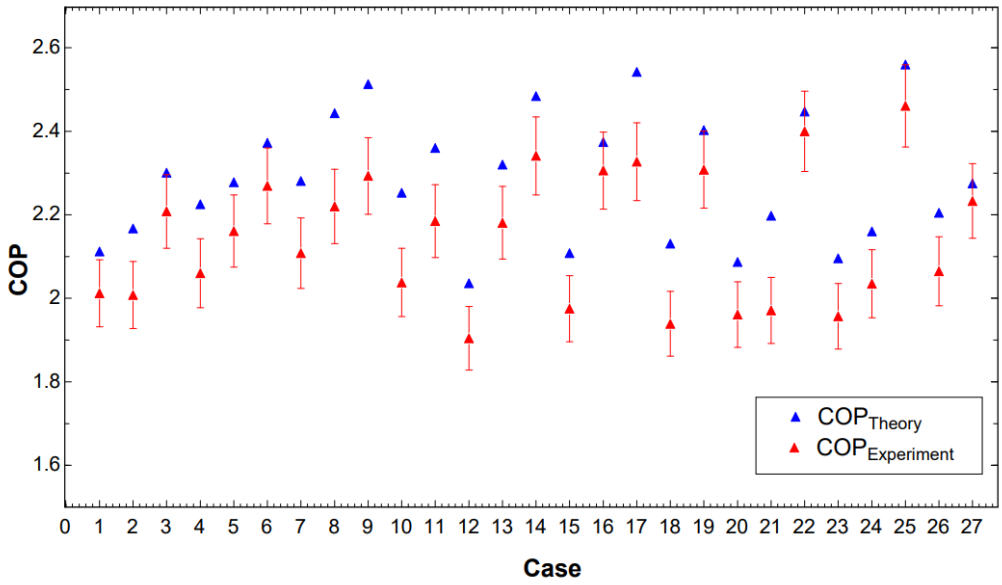


Figure 6. Diagram of comparison table between COP_{Theory} and COP_{Actual}.

From the ANOVA variance analysis table, the COP is evaluated based on the given factors; the changes in the factors will change the calculation results. The results can predict the change in the COP based on the above factors. Furthermore, a regression equation can predict the COP based on the change in the F-value and the *p*-value and predict the COP based on the thermodynamic parameters of the cycle. Linear regression equations of both actual and theoretical cases are as follows:

In theory: COP = 1.9008 − 0.01491A + 0.07763B + 0.02759C + 0.00272D − 0.04950E + 0.14946F. With R^2 = 0.9745.

In actual: COP = 1.8126 + 0.0029A + 0.0754B + 0.0092C − 0.0191D − 0.0582E + 0.1562F. With R^2 = 0.9383.

From the above two equations, the COP can be predicted in advance under operating conditions. Table 15 shows the COP which can be predicted by the regression equation and the degree of difference between the theory calculation and the prediction by the regression equation in the ANOVA method.

From Table 15, the prediction results and the analysis results obtained by the experimental method are almost the same. Prediction has different percentages, with the smaller calculated COP representing the more accurate results; the equation depends heavily on the noise of the calculated parameters. The highest in predicting the results was in the L17 case and in the theoretical case it was L12. From Taguchi's analysis a set of setting data was obtained as $A_3B_3C_2D_1E_1F_3$ at the highest and an optimal COP of 2.457 corresponding to the case L25: T_{sh_R744} = 7 °C, T_{e_R134a} = 5 °C, T_{sc_R744} = 3 °C, T_{sc_R134a} = 4 °C, T_{c_R744} = 6 °C, and T_{e_R744} = −23 °C. Based on the thermodynamic parameters presented in Table 2, this study has developed a regression equation with a relatively high R^2 value, indicating strong correlation. The deviation between theoretical predictions and experimental results remains within acceptable limits. The refrigeration system utilizing R134a/R744 can reliably apply the theoretical regression equation to interpolate the coefficient of performance (COP) under given operating conditions.

Table 15. Results comparing $COP_{Experiment}$ and COP_{Theory} with predicted COP_{Actual}.

Case	COP_{Theory}	$COP_{Experiment}$	Predicted COP_{Actual}	Difference (%)
1	2.122	2.012	1.979	1.640
2	2.167	2.008	2.077	3.436
3	2.301	2.208	2.175	1.495
4	2.225	2.06	2.045	0.752
5	2.278	2.161	2.143	0.856
6	2.372	2.269	2.241	1.256
7	2.281	2.108	2.110	0.095
8	2.443	2.22	2.208	0.541
9	2.513	2.293	2.306	0.567
10	2.253	2.038	2.109	3.489
11	2.360	2.185	2.207	1.011
12	2.036	1.904	1.837	3.545
13	2.320	2.181	2.232	2.334
14	2.484	2.341	2.330	0.474
15	2.108	1.975	1.959	0.795
16	2.374	2.306	2.270	1.570
17	2.542	2.327	2.368	1.753
18	2.131	1.939	1.997	3.002
19	2.403	2.308	2.297	0.498
20	2.087	1.961	1.926	1.790
21	2.198	1.971	2.024	2.684
22	2.447	2.4	2.334	2.733
23	2.096	1.957	1.964	0.347
24	2.160	2.035	2.062	1.317
25	2.560	2.461	2.457	0.154
26	2.205	2.065	2.087	1.046
27	2.275	2.233	2.185	2.167

3.4. Verify

From Table 11, based on the evaluation level of each individual factor, the combination set of $A_3B_3C_2D_1E_1F_3$ gives the COP value according to S/N; it is the most optimal parameter from Taguchi's analysis. Corresponding to that value, the operating conditions of the system are as follows:

With the most optimal dataset from the experiment: T_{sh_R744} = 7 °C, T_{e_R134a} = 5 °C, T_{sc_R744} = 3 °C, T_{sc_R134a} = 4 °C, T_{c_R744} = 6 °C, and T_{e_R744} = −23 °C. After collecting data and analyzing the results of five tests based on the above optimal set of parameters in the changing HTC condensation temperature during a day, the COP results are shown in Table 16 as below.

Table 16. Experimental results for the most optimal combination.

Factor	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
A	6.38	6.43	6.35	6.57	6.3
B	5	5	5	5	5
C	2.88	2.93	2.75	3.07	2.8
D	4.14	3.89	4.06	4.19	4.01
E	7	7	7	7	7
F	−23	−23	−23	−23	−23
COP	**2.475**	**2.477**	**2.473**	**2.484**	**2.48**

4. Conclusions

Based on theoretical and experimental analysis by the Taguchi method and ANOVA variance analysis, according to the L27 orthogonal table and conducting experiments in 27 corresponding cases, the influence factors on the COP of the cascade refrigeration system have been shown.

Through the calculation and analysis of data according to both the Taguchi and ANOVA methods, it is indicated that the evaporating temperature at LTC is the factor with the greatest influence on the COP with a 1st rank and a contribution percentage of 69.18%. In addition, the results show that the subcooling temperature of HTC and the superheating temperature of HTC have affected insignificantly on the COP.

Based on the experimental dataset, the research has given a set of data for the highest COP of 2.461 corresponding to the L25 case within the set $A_3B_3C_2D_1E_1F_3$.

This study has given a regression equation for the influence of operating modes both in theory and in experiments. Experimental verification with theory-based optimization has the highest error of 3.54%.

For future research directions, the algorithm employed in this study can be further applied for optimization by incorporating an auxiliary thermoelectric cooling device. Additionally, evaluating the isentropic compression efficiency and exergy efficiency under operational conditions influenced by ambient temperature, humidity, and solar radiation is recommended. Furthermore, a comparative analysis of environmental performance indicators such as the Total Equivalent Warming Impact (TEWI) and Economic Analysis should be conducted across different refrigerant pairs.

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Abbreviations

The following abbreviations are used in this manuscript:

T	The absolute temperature (°C)
m	Mass flow rate (kg/s)
W	Work of adiabatic compression (W)
COP	Coefficient of performance
MS	Mean square
MSE	Mean square error
i	Experiment number
y_i	The data observed in experiment number i
$\hat{y}_i$	The i-th response value
$L_{f,i}$	The number of the levels
Q_0	Cooling capacity (W)
Q_k	Condensing capacity (W)
h	Enthalpy of fluid (kJ/kg)
S/N	The signal to noise
DOF	The total degree of freedom
n	The number of experiments

$\overline{y}$	The average response value
F	The F_value
$n_{L,i}$	The number of factors
T_{sh_R744}	Superheating temperature of low temperature cycle (°C)
T_{sc_R744}	Subcooling temperature of low temperature cycle (°C)
T_{e_R744}	Evaporating temperature of low temperature cycle (°C)
T_{c_R744}	Condensing temperature of low temperature cycle (°C)
T_{sh_R134a}	Superheating temperature of high temperature cycle (°C)
T_{sc_R134a}	Subcooling temperature of high temperature cycle (°C)
T_{e_R134a}	Evaporating temperature of high temperature cycle (°C)
T_{c_R134a}	Condensing temperature of high temperature cycle (°C)
LTC	Low temperature cycle
HTC	High temperature cycle

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