MODELLING AND OPTIMIZATION OF COEFFICIENT OF PERFORMANCE OF LOWER TEMPERATURE CYCLE OF TWO-STEP REFRIGERATION SYSTEMS

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ABSTRACT

The coefficient of performance (COP) of a single-stage refrigeration system is low, thus there is a need for two-step refrigeration systems when there is a desire to have an evaporator temperature that is below -25 ºC. The COP of the lower temperature cycle of the two-step refrigeration systems is a function of the COP of the refrigeration systems.This research aimed at optimizing COP of the lower temperature cycle of two-step refrigeration systems using eco-friendly refrigerants.Thermodynamic analysis of these refrigeration systems was performed by varying seven operating parameters. R-134a was used in the high-temperature cycle (HTC) and R-23 was used in the low-temperature cycle (LTC). The coefficient of performance of the lower temperature cycle (COP.REF[LTC]) of the refrigeration systems was optimized using Half Factorial Design of Design-Expert 12.0.1. The influence of the condensing temperature ($T_{C,HTC}$),evaporating temperature ($T_{E,HTC}$), cascade temperature difference ($\Delta T_{CAS,DIFF}$), evaporating temperature ($T_{E,LTC}$), superheating temperature ($T_{SUP,LTC}$), sub-cooling temperature ($T_{SUB,LTC}$), and refrigerant mass Flow rate ($\dot{m}_{HTC}$)was investigated on the values of COP.REF[LTC] of the refrigeration systems. The highest value of COP.REF[LTC] (18.1) was obtained under optimum conditions of the 30 $T_{C,HTC}$ºC , -40 $T_{E,HTC}$ºC, 0 $\Delta T_{CAS,DIFF}$ºC, -50 $T_{E,LTC}$ºC, 0 $T_{SUP,LTC}$ºC, 20 $T_{SUB,LTC}$ºC and 0.01 $\dot{m}_{HTC}$ kg/s.The study revealed that all the factors having interaction with TC[HTC] and TE[HTC] have a great influence on the value of COP.REF[LTC]

Keywords: COP, Sub-cooling, Superheating, Refrigeration, Cascade, Refrigerants.

1. Introduction

Refrigeration technology plays an important role in human production and life; it is widely used in daily lives, commerce, and industrial production. The traditional single-stage compression refrigeration system and absorption refrigeration system are two basic forms of the refrigeration technology. Single-stage compression refrigeration system is used in air conditioning, refrigerator, food storage, and transportation (Suman and Singh, 2020). However, rapid freezing and the storage of frozen food require rather low temperatures in the evaporator (-40 to -50 ºC), high compression ratio, or the high temperature difference in heat exchanger (Mishra, 2018). In addition, the Coefficient of Performance (COP) and the volume efficiency of single-stage compression refrigeration system will be reduced by high output temperature and pressure of the refrigerants (Dhumal and Dange, 2014). Single-stage absorption refrigeration system is commonly used for freezing applications and can effectively convert the low-grade waste heat into high-grade cold energy. However, when the temperature difference between cold energy and heat source increases, both COP and economy of thesingle-stage absorption refrigeration system will decrease (Tsamos*et al,* 2016); thus, the application of refrigeration system at a low evaporation temperature is seriously limited. Therefore, there is a need to have two-step refrigeration systems to achieve lower refrigeration temperatures below 25 ºC. It has a wide range of applications, for example in the field of hypothermal medicine, cryopreservation for an instrument, and cryogenics, e.g. liquefied gas (Suresh *et al*, 2016). It is also widely used in the storage and distribution of food, supermarkets, small refrigeration devices, air conditioning, etc. The system can conform to not only a suitable evaporation pressure at a lower evaporation temperature but also a moderate condensation pressure at ambient temperature. (Suresh *et al*, 2016; Mishra, 2017).

2. Methodology

2.1 Performance Analysis

The two-step refrigeration system was modelled modularly incorporating each individual process of the cycle (Figure 2.1). Its thermodynamic analysis wasconducted. A steady flow energy equation and the mass balanced equation was employed. The parameters considered for the analysis are;

1. Isentropic efficiency (η_{isen})=0.85 for both H_{TC} and L_{TC} compressor
2. Effectiveness of heat exchanger ($\sum_{cc}$)=1

2.2 Analysis for Selection of Refrigerants

Factors considered for the choice of refrigerants are stated below:

i. Ozone Depletion Potential (ODP)
ii. Global Warming Potential (GWP)
iii. Eco-Friendliness
iv. Good performance properties

Refrigerant R-134a was chosen for the high-temperature cycle (HTC) because it is economically viable, environmentally friendly, and energy-efficient. It has excellent thermodynamics and transport properties, while refrigerant R-23 of a lower boiling point was chosen forthe low-temperature cycle (LTC) because it has low critical pressureandis also widely available.

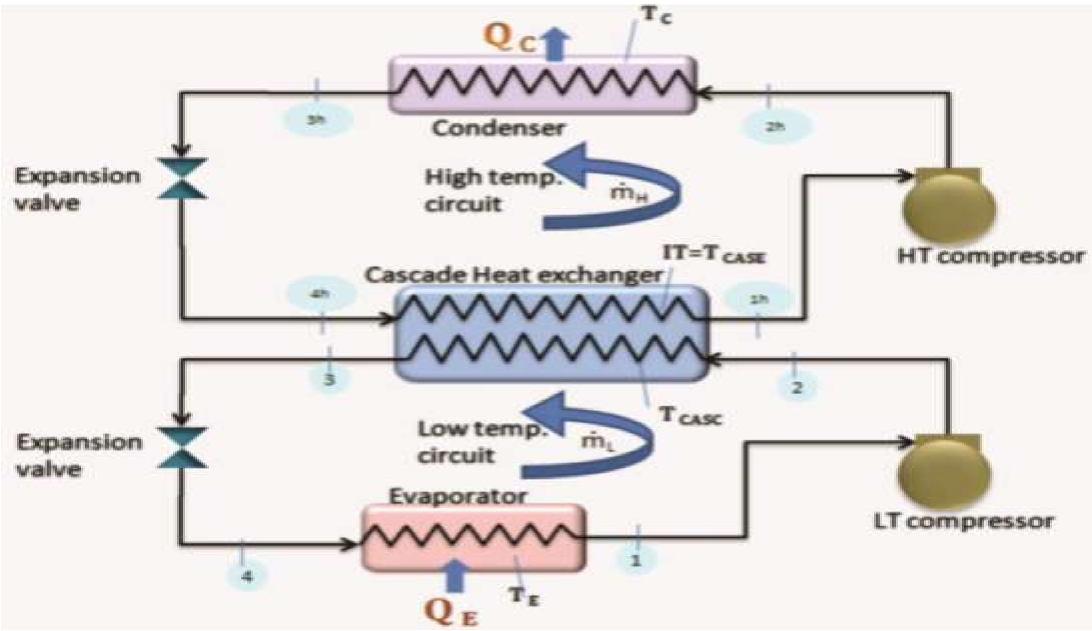


Figure 2.1: Schematic Diagram of a Cascade Refrigeration System

3.4 Process Optimization of Two-Step Refrigeration Systems

Condensing temperature ($T_{C,HTC}$), evaporating temperature ($T_{E,HTC}$), cascade temperature difference ($\Delta T_{CAS,DIFF}$), evaporating temperature ($T_{E,LTC}$), superheating temperature ($T_{SUP,LTC}$), sub-cooling temperature ($T_{SUB,LTC}$), and refrigerant mass flow rate ($\dot{m}_{HTC}$) were optimized using Half Factorial Design (HFD) under the Factorial Design of the Design of Experiment (DOE) software (12.0.1). The parameter levels that were considered in this study are stated in Table 2.1. These parameters levels generated 30 experimental runs.A computational model was developed for the refrigeration systems usingthe Engineering Equation Solver (EES). The effect of these seven parameters on COP.REF[LTC] was determined at optimum conditions.

The validation of experiments was carried out by investigating the percentage error between predicted and actual values (equation 1).

$$Error = \frac{(Actual\,Value - Predicted\,Value)\,X\,100}{Actual\,Value} \qquad (1)$$

3. Results and discussion

3.1 Optimization of Cascade Refrigeration Systems with Refrigerants R-134 / R-23

The experimental design for the two-step refrigeration systems with refrigerants R-134/ R-23.

The design generated thirty (30) experimental runs and experimental run

14 (30 $T_{C,HTC}$°C , -40 $T_{E,HTC}$°C, 0 $\Delta T_{CAS,DIFF}$°C, -50 $T_{E,LTC}$°C, 0 $T_{SUP,LTC}$°C, 20 $T_{SUB,LTC}$°C and 0.01 $\dot{m}_{HTC}$kg/s)

2.1: Parameters Level Selected for Half Factorial Design (HFD) for Cascade Refrigeration System

	Units	Level	
		Low	High
HTC Condensing Temperature ($T_{C,HTC}$)	ºC	30	70
HTC Evaporating Temperature ($T_{E,HTC}$)	ºC	-20	-40
Cascade Temperature Difference ($\Delta T_{CAS,DIFF}$)	ºC	0	15
LTC Evaporating Temperature ($T_{E,LTC}$)	ºC	-50	-100
LTC Superheating Temperature ($T_{SUP,LTC}$)	ºC	0	20
LTC Sub cooling Temperature ($T_{SUB,LTC}$)	ºC	0	20
HTC Refrigerant Mass Flow Rate (M_{HTC})	kg/s	0.01	0.11

has the highest value (18.1) of coefficient of performance for cascade refrigeration systems (COP.REF[LTC]), while experimental run 22 (30 $T_{C,HTC}$ºC , -20 $T_{E,HTC}$ºC, 15 $\Delta T_{CAS,DIFF}$ºC, -100 $T_{E,LTC}$ºC, 0 $T_{SUP,LTC}$ºC, 0 $T_{SUB,LTC}$ºC and 0.01 $\dot{m}_{HTC}$ kg/s) has the least value (0.8616) of COP.REF[LTC] (Table 3.1). The final tool factor interaction (2FI) empiricalmodel in terms of coded factors for the COP.REF[LTC] for both the significant and insignificant terms is expressed in equation 2.

$$COP.REF[LTC] = 4.61 - 0.3650A - 1.85B - 1.61C + 2.61D - 0.4363E - 0.1096F - 0.4047G + 0.1262AB + 0.5285AC - 0.7322AD + 0.5907AE - 0.1268AF - 0.0264AG + 1.07BC - 1.67BD + 0.5680BE - 0.1105BF + 0.1237BG - 1.09CD + 0.5302CE + 0.1625CF + 0.3640CG - 0.0658DE + 0.2946EF + 0.2989EG + 0.4738BCD \quad (2)$$

Where A= HTC CondensingTemperature [$T_{C,HTC}$] (ºC), B = HTC Evaporating Temperature [$T_{E,HTC}$] (ºC), C = Cascade Temperature Difference [$\Delta T_{CAS,DIFF}$] (ºC), D = LTC Evaporating Temperature [$T_{E,LTC}$] (ºC), E = LTC Superheating Temperature [$T_{SUP,LTC}$] (ºC), F = LTC Sub cooling Temperature [$T_{SUB,LTC}$] (ºC), and G = HTC Refrigerant Mass Flow Rate [$\dot{m}_{HTC}$] (kg/s).

The quality of the models developed was evaluated based on the R^2value and the models developed seems to be the best at low standard deviation and high R^2that is closer to
unity thus making predicted value closer to the actual value of the response (Mohd*et al*., 2011). In this experiment, R^2 value for Eq. (2) as shown in Fig. 4.1a was 0.9981, Standard deviation value was 0.6955, mean value was 4.63, Coefficient of variation (C.V.) was 15.03, Adeq Precision was 28.6290, Adjusted (Adj) R^2 was 0.9817, Predicted (Pred) R^2 was 0.7035. High value of R^2 for Eq. (2) was an indication that the predicted value for COP.REF[LTC] would be more accurate and closer to its actual value (Montgomery, 2005). Figure 3.1b showed the effects of the model terms with respect to half normal % probability, while Figure 3.1c showed the effect of the model terms with respect to normal % probability.

The low value of standard deviation for COP.REF[LTC] was an indication that the predicted value for the model was considered as suitable to correlate the experimental data (Montgomery, 2005). “Adeq Precision” which measures the signal to noise ratio is 28.629 (greater than 4) and is desirable adequate signal necessary for the model to navigate the design space. Model terms are considered as significant, if the value ofProb>F less than 0.05. TheModel F-value of 60.81 (Table 3.2) implies the model is significant and that thereis only 0.29% chance that Model F-Value could occur due to noise (Mohd*et al.,* 2011). P values less than 0.05 indicate model terms are significant and values greater than 0.10 indicate the modelterms are not significant, thus A, B, AG, CG, DG, EF and BCD are significant model terms.

Table 3.1: Experimental Data for Refrigerants R – 134a / R – 23

Run	PARAMETERS 1 A:TC[HTC] ºC	PARAMETERS 2 B:TE[HTC] ºC	PARAMETERS 3 C:TCAS [DIFF] ºC	PARAMETERS 4 D:TE[LTC]º C	PARAMETERS 5 :TSUP[LTC]º C	PARAMETERS 6 F:TSUB [LTC] ºC	PARAMETERS 7 G:M[HTC] kg/s	Response COP. REF[LTC]
1	70	-40	15	-50	0	0	0.01	6.503
2	70	-20	0	-50	0	20	0.11	1.33
3	30	-20	0	-100	0	20	0.11	1.412
4	30	-40	0	-50	0	0	0.11	17.71
5	70	-40	15	-100	20	0	0.01	1.333
6	70	-20	0	-100	20	20	0.11	1.459
7	70	-20	15	-50	20	20	0.11	3.549
8	30	-40	15	-100	0	0	0.11	1.3
9	70	-20	0	-50	0	0	0.01	5.244
10	70	-40	0	-100	0	20	0.11	2.068
11	30	-20	0	-50	20	20	0.01	5.525
12	70	-20	15	-100	0	20	0.11	1.1
13	30	-40	0	-50	20	20	0.11	14.32
14	30	-40	0	-50	0	20	0.01	18.10
15	70	-40	0	-100	20	0	0.11	1.82
16	30	-20	15	-100	20	20	0.01	1.15
17	70	-20	0	-100	0	0	0.11	1.173
18	30	-20	0	-100	20	0	0.01	1.233
19	70	-40	15	-50	20	0	0.11	5.485
20	70	-20	0	-100	0	20	0.01	1.412
21	70	-40	15	-50	20	20	0.01	6.332
22	30	-20	15	-100	0	0	0.01	0.8616
23	30	-40	0	-100	20	20	0.01	2.078
24	30	-40	15	-50	20	0	0.01	5.485
25	70	-40	0	-50	20	0	0.01	12.68
26	30	-20	15	-50	0	0	0.11	3.103
27	30	-20	15	-100	20	0	0.11	0.9237
28	30	-40	15	-50	0	20	0.11	7.595
29	70	-20	15	-50	20	0	0.01	2.917
30	30	-40	15	-100	0	20	0.01	1.543

Table 3.3 indicated diagnostics design between the actual value and residual value.
Figure 3.2a, d, 3.3a, d, 3.4a, d, 3.5a, d, 3.6a, d, 3.7a, d, 3.8a, d, 3.9a, d, and 3.10a, dshowed the factors interactionsplots, Fig. 3.2b, e, 3.3b, e, 3.4b, e, 3.5b, e, 3.6b, e, 3.7b, e, 3.8b, e, 3.9b, e, and 3.10b, eshowedCOP.REF[LTC]value; while Fig. 3.2c, f, 3.3c, f, 3.4c, f, 3.5c, f, 3.6c, f, 3.7c, f, 3.8c, f, 3.9c, f, and 3.10c, f showed the 3D factors interactions plots for the interactive effects among all the selected factors on the values of COP.REF[LTC]. Figure 3.2a shows interaction of TC[HTC] and TE[HTC]. The value of COP.REF[LTC]decreased as TC[HTC] and TE[HTC] values increased. Its COP.REF[DIFF] and 3D linear interaction isevident in Fig. 3.2b and c.

Similar trend was observed in the interaction between TC[HTC] and TCAS[DIFF] (Fig. 3.2d, e, and f), TC[HTC] and TE[LTC] (Fig. 3.3a, b, and c), TC[HTC] and TSUP[LTC] (Fig. 3.3d, e, and f), TC[HTC] and TSUB[LTC] (Fig. 3.4a, b, and c), TC[HTC] and ṁ[HTC] (Fig. 3.4d, e, and f), TE[HTC] and TCAS[DIFF] (Fig. 3.5a, b, and c), TE[HTC] and TE[LTC] (Fig. 3.5d, e, and f), TE[HTC] and TSUP[LTC] (Fig. 3.6a, b, and c), TE[HTC] and TSUB[LTC] (Fig. 3.6d, e, and f), TE[HTC] and ṁ[HTC] (Fig. 3.7a, b, and c), TCAS[DIFF] and TE[LTC] (Fig. 3.7d, e, and f), TCAS[DIFF] and TSUP[LTC] (Fig. 3.8a, b, and c), TCAS[DIFF] and TSUB[LTC] (Fig. 3.8d, e, and f), TCAS[HTC] and ṁ[HTC] (Fig. 3.9a, b, and c), TSUP[LTC] and TSUP[LTC] (Fig. 3.10a, b, and c), as well as TSUP[LTC] and ṁ[HTC] (Fig. 3.10d, e, and f).

The interaction between TE[LTC] and TSUP[LTC] shows a sharp increase in the value of COP.REF[DIFF] (Fig. 3.9d,e, and f). This suggests that increase inthe TE[LTC] and TSUP[LTC] or either is favourable for the increase in value of COP.REF[LTC].

3.2 Analysis of Variance (ANOVA) of COP.REF[LTC]

The significance and adequacy of the model was also justified through analysis of variance (ANOVA). Essentially, allthe factors having interactionwith TC[HTC] and TE[HTC]have great influence on the value of COP.REF[LTC] thus indicating the importance of these two factors in determining the value of COP of the lower circuit of two step refrigeration systems. The value of COP.REF[LTC] is therefore influenced by Condensing Temperature ($T_{C,HTC}$), Evaporating Temperature ($T_{E,HTC}$), Cascade Temperature Difference ($\Delta T_{CAS,DIFF}$), Evaporating Temperature ($T_{E,LTC}$), Superheating Temperature ($T_{SUP,LTC}$), Sub-cooling Te1perature ($T_{SUB,LTC}$), and Refrigerant Mass Flow Rate ($\dot{m}_{HTC}$). Figure 3.11 further indicates that the value ofCOP.REF[LTC] is effectivelyinfluenced by TC[HTC], TE[HTC] and TCAS[DIFF] while keeping the TE[LTC] (-50 ºC), TSUP[LTC] (0 ºC), TSUB[LTC] (20 ºC), and ṁ[HTC] (0.01kg/s) constant.

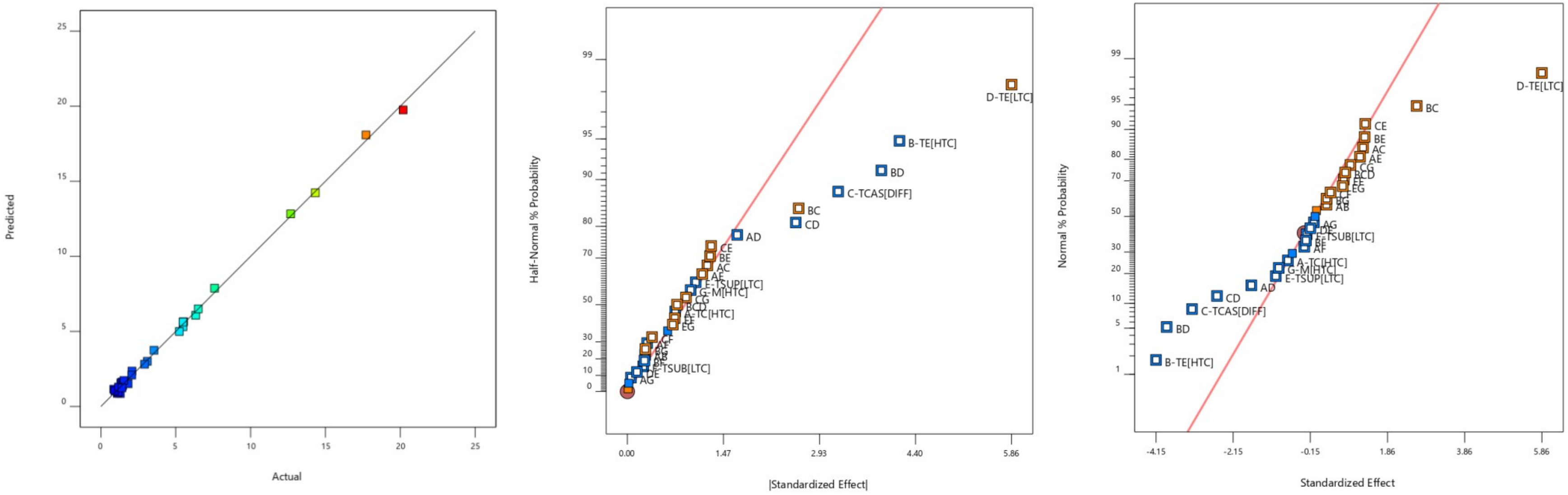


Figure 3.1

a: Graph of predicted COP.REF[LTC] against its actual value

b: effects of the model terms with respect to half normal % probability

c: effect of the model terms with respect to normal % probability

Table 3.2: ANOVA for selected factorial model for COP.REF[LTC]

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	764.84	26	29.42	60.81	0.0029	*
A	2.03	1	2.03	4.20	0.1327	
B	65.79	1	65.79	136.01	0.0014	*
C	39.49	1	39.49	81.64	0.0029	*
D	131.14	1	131.14	271.10	0.0005	*
E	4.15	1	4.15	8.58	0.0610	
F	0.2247	1	0.2247	0.4645	0.5444	
G	3.56	1	3.56	7.36	0.0730	
AB	0.2836	1	0.2836	0.5863	0.4996	
AC	5.69	1	5.69	11.76	0.0416	*
AD	10.73	1	10.73	22.18	0.0181	*
AE	4.98	1	4.98	10.29	0.0490	*
AF	0.3475	1	0.3475	0.7185	0.4589	
AG	0.0114	1	0.0114	0.0236	0.8876	*
BC	26.08	1	26.08	53.92	0.0052	*
BD	57.31	1	57.31	118.48	0.0017	*
BE	6.08	1	6.08	12.58	0.0382	*
BF	0.2600	1	0.2600	0.5376	0.5165	
BG	0.2889	1	0.2889	0.5972	0.4960	
CD	25.19	1	25.19	52.07	0.0055	*
CE	6.23	1	6.23	12.88	0.0371	*
CF	0.5429	1	0.5429	1.12	0.3672	
CG	3.05	1	3.05	6.30	0.0869	
DE	0.0817	1	0.0817	0.1688	0.7087	
EF	2.00	1	2.00	4.13	0.1351	
EG	1.84	1	1.84	3.79	0.1466	
BCD	2.20	1	2.20	4.54	0.1229	
Residual	1.45	3	0.4837			
Cor Total	766.29	29				

* Significant at $p < 0.05$, R^2 is 0.9981, A-TC[HTC], B-TE[HTC], C-TCAS[DIFF],
D-TE[LTC], E-TSUP[LTC], F-TSUB[LTC], G-M[HTC]

Table 3.3: Diagnostics design between the actual value and residual value

Run Order	Actual Value	Predicted Value	Residual
1	6.50	6.50	0.0043
2	1.33	1.45	-0.1190
3	1.41	1.24	0.1700
4	17.71	18.08	-0.3746
5	1.33	1.58	-0.2478
6	1.46	1.39	0.0722
7	3.55	3.75	-0.1968
8	1.30	0.8652	0.4348
9	5.24	5.00	0.2464
10	2.07	2.09	-0.0262
11	5.53	5.65	-0.1275
12	1.10	0.8741	0.2259
13	14.32	14.23	0.0892
14	18.1	17.76	0.3400
15	1.82	1.51	0.3073
16	1.15	0.9624	0.1876
17	1.17	1.29	-0.1190
18	1.23	1.14	0.0892
19	5.49	5.63	-0.1445
20	1.41	1.62	-0.2124
21	6.33	6.08	0.2563
22	0.8616	1.15	-0.2860
23	2.08	2.36	-0.2811
24	5.49	5.32	0.1700
25	12.68	12.83	-0.1494
26	3.10	3.01	0.0941
27	0.9237	1.05	-0.1275
28	7.59	7.88	-0.2860
29	2.92	2.81	0.1026
30	1.54	1.73	-0.1870

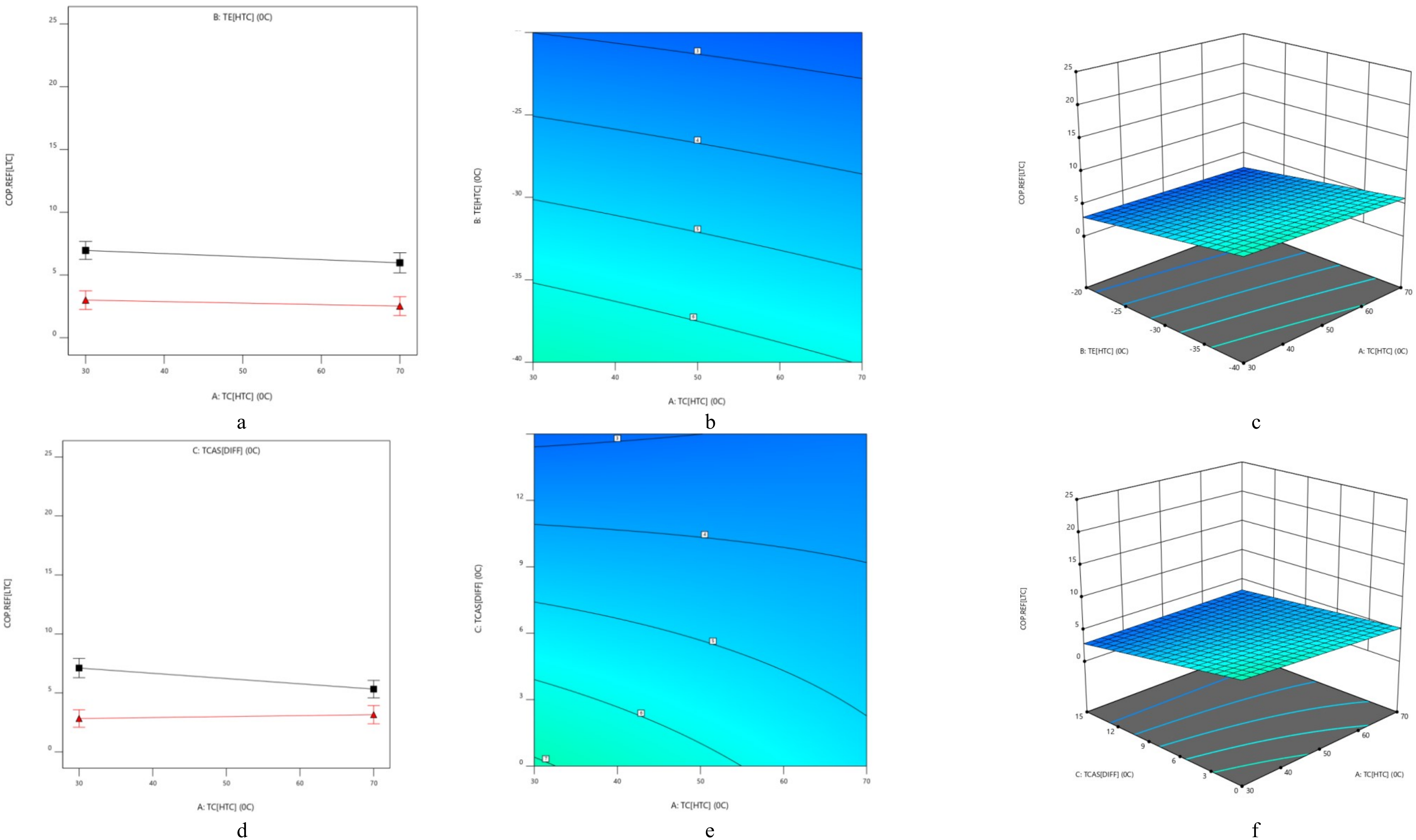
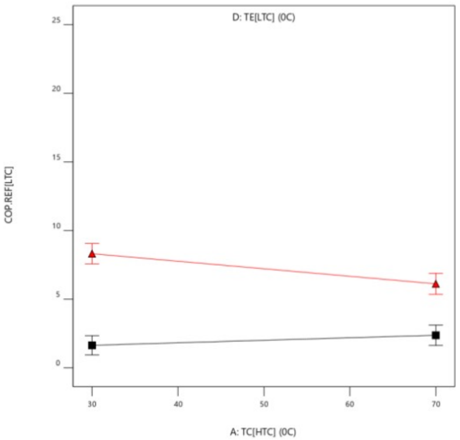


Figure 3.2: (a) Interaction, (b) COP.REF[LTC] and (c) 3D surface plot of TC[HTC] against TE[HTC] on COP.REF[LTC]
(d) Interaction, (e) COP.REF[LTC] and (f) 3D surface plot of TC[HTC] against TCAS[DIFF] on COP.REF[LTC]



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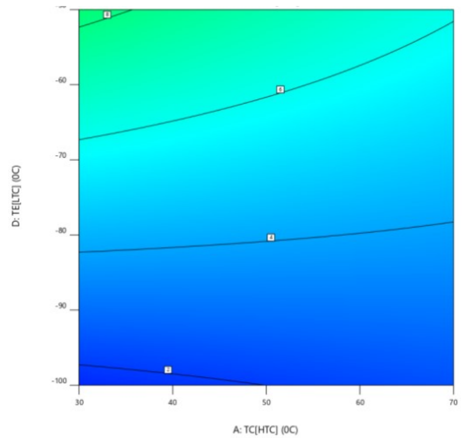

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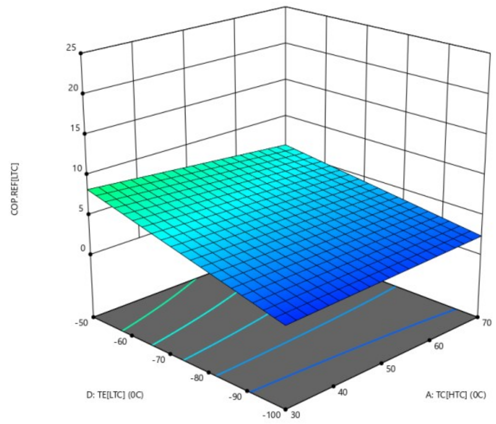

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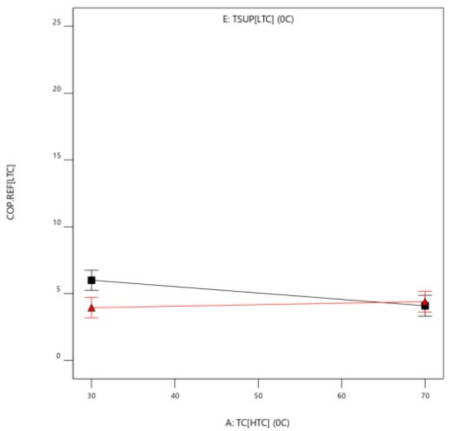

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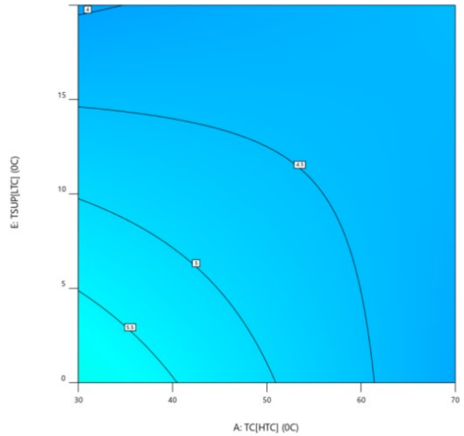

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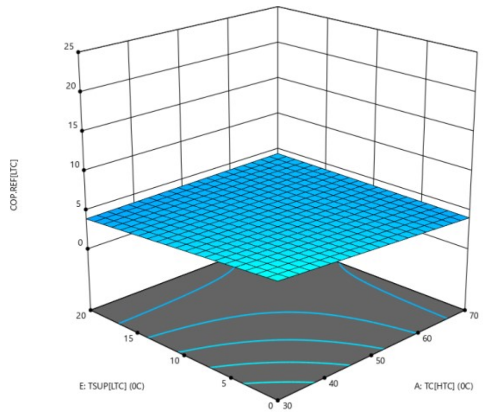

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Figure 3.3: (a) Interaction, (b) COP.REF[LTC] and (c) 3D surface plot of TC[HTC] against TE[LTC] on COP.REF[LTC]
(d) Interaction, (e) COP.REF[LTC] and (f) 3D surface plot of TC[HTC] against TSUP[LTC] on COP.REF[LTC]

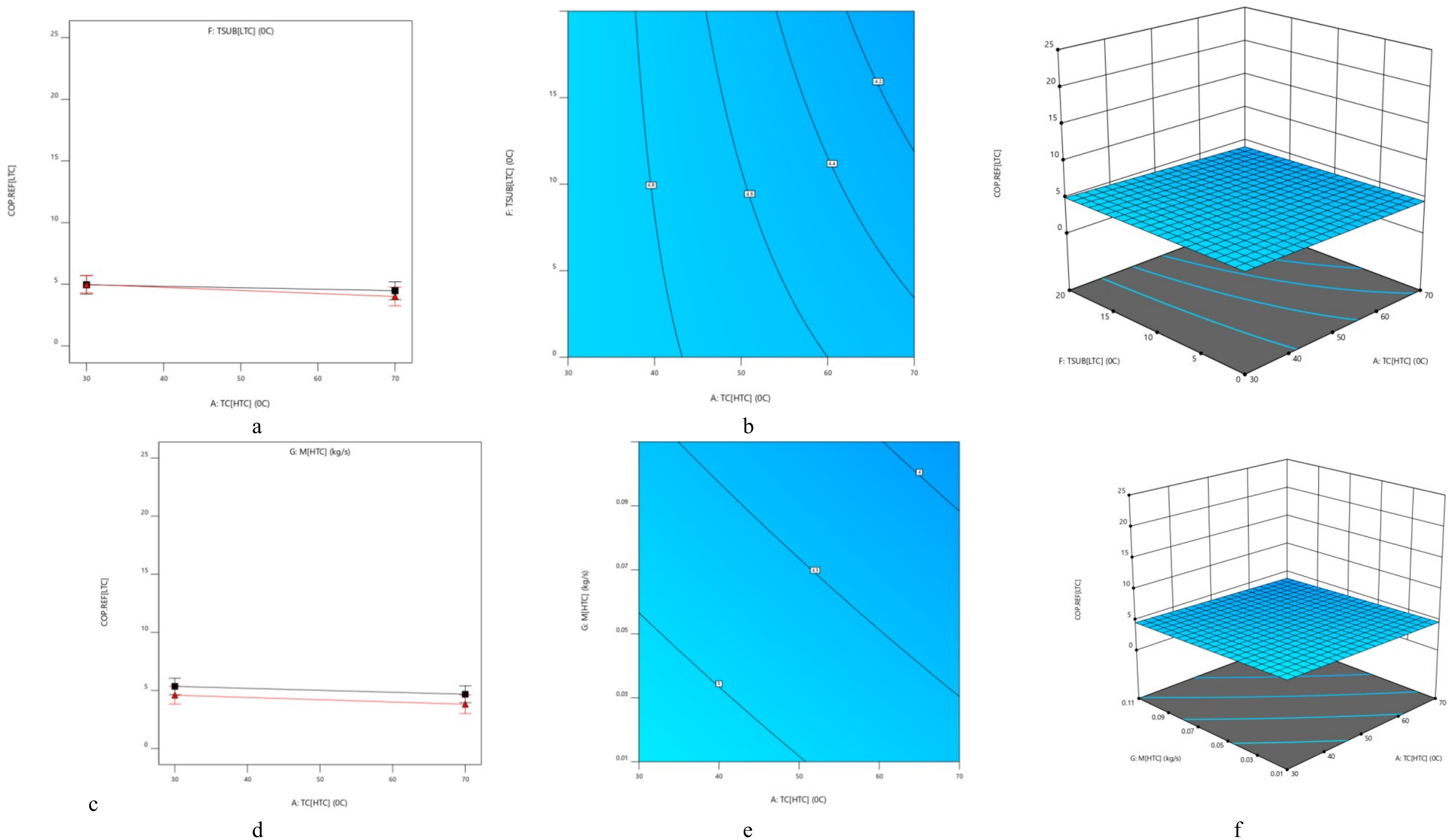
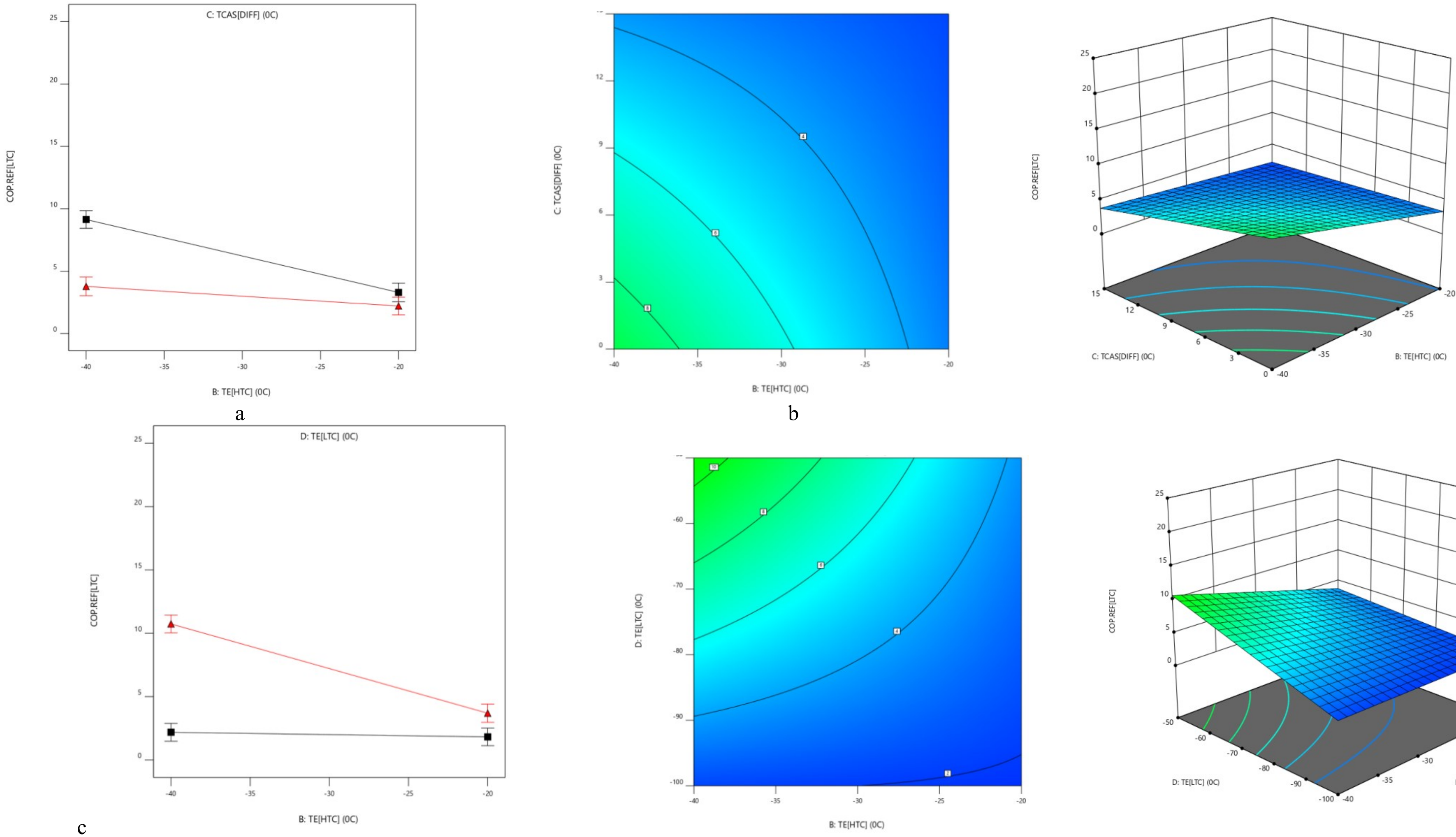


Figure 3.4: (a) Interaction, (b) COP.REF[LTC] and (c) 3D surface plot of TC[HTC] against TSU[LTC] on COP.REF[LTC]
(d) Interaction, (e) COP.REF[LTC] and (f) 3D surface plot of TC[HTC] against M[HTC] on COP.REF[LTC]



a b c d e f

Figure 3.5: (a) Interaction, (b) COP.REF[LTC] and (c) 3D surface plot of TE[HTC] against TCAS[DIFF] on COP.REF[LTC] (d) Interaction, (e) COP.REF[LTC] and (f) 3D surface plot of TE[HTC] against TE[LTC] on COP.REF[LTC]

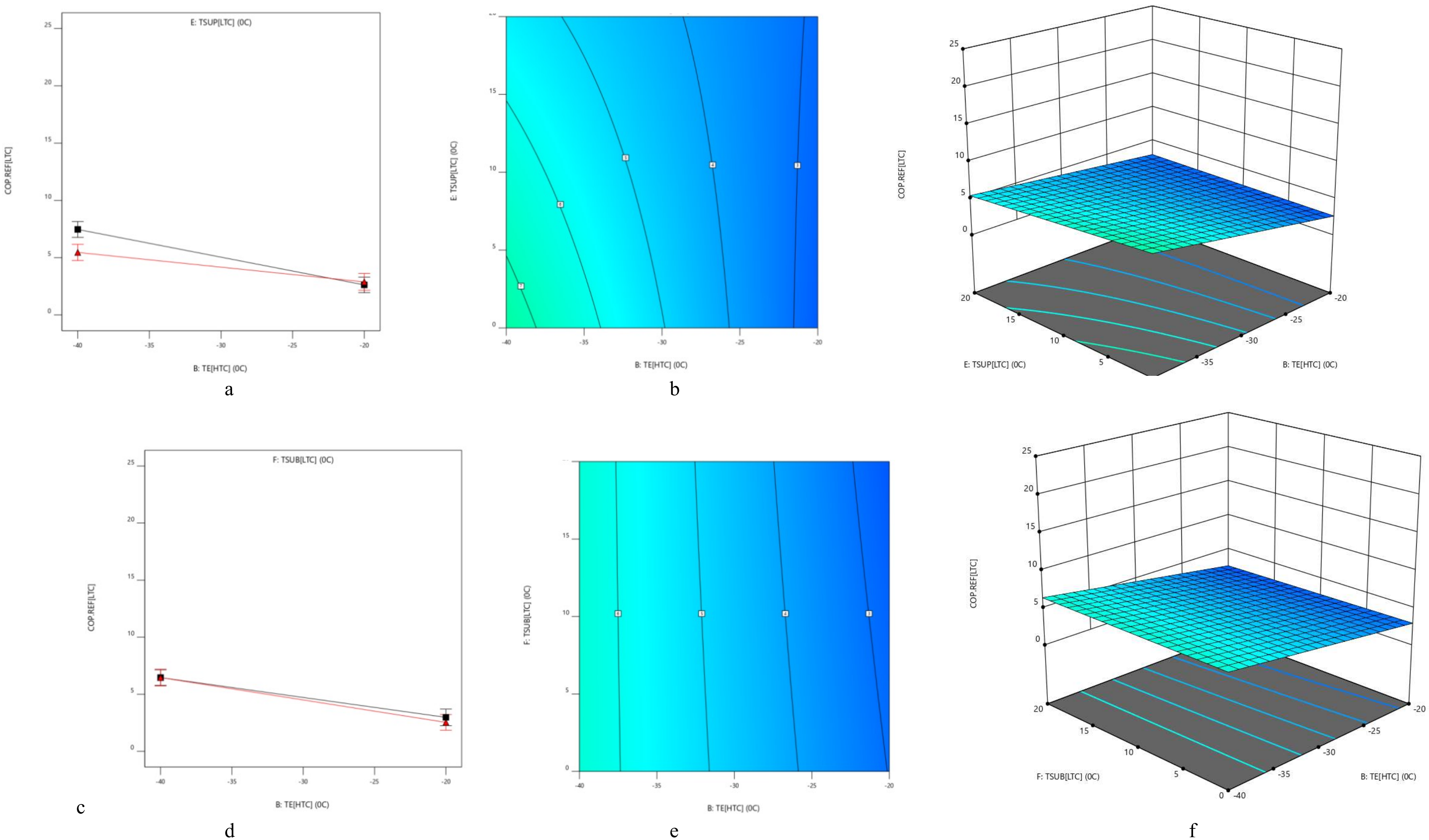
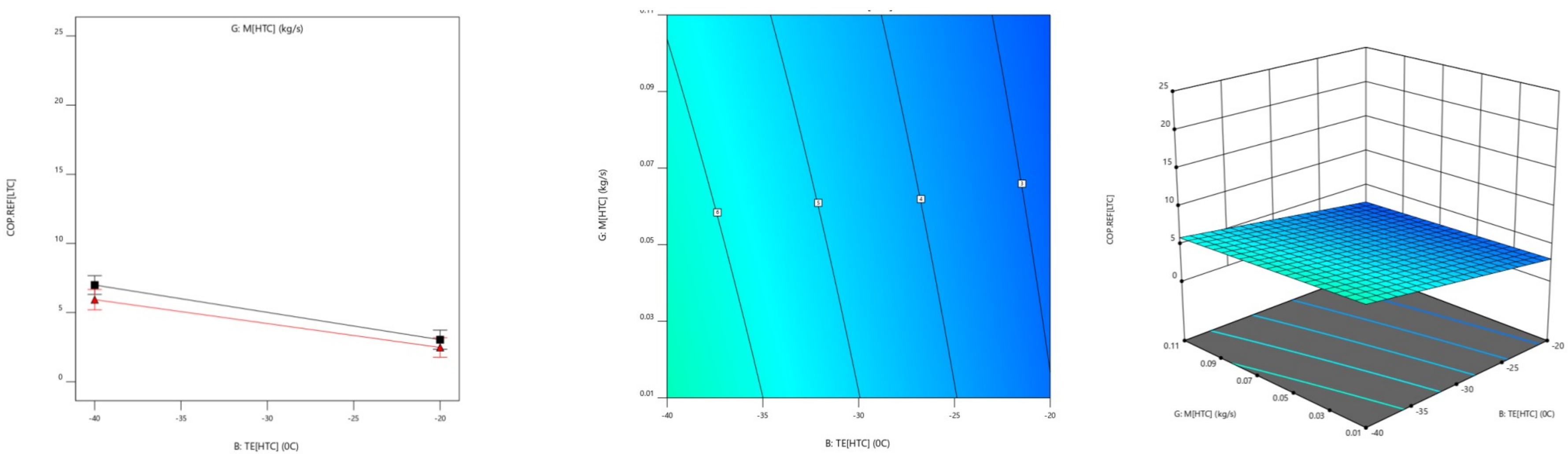
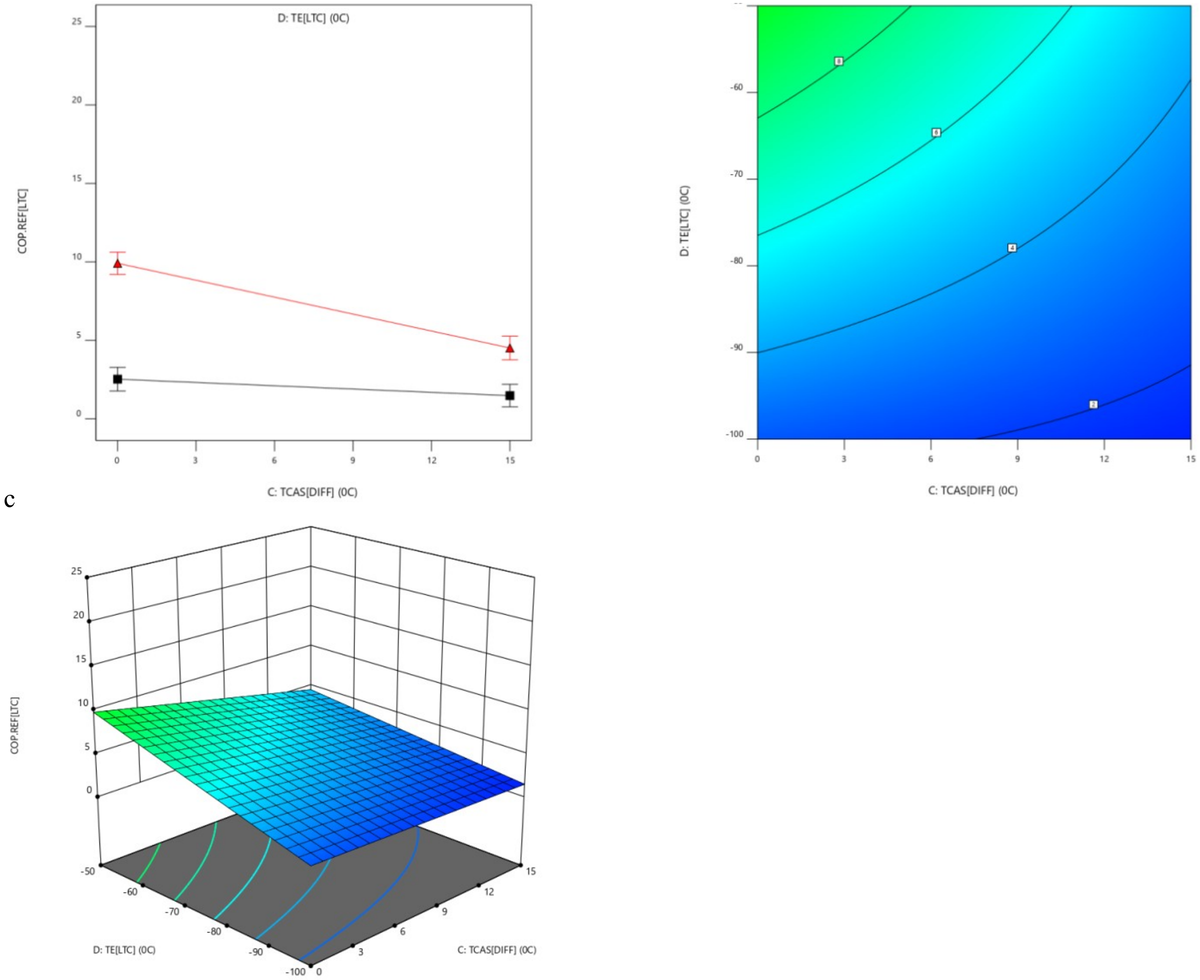


Figure 3.6: (a) Interaction, (b) COP.REF[LTC] and (c) 3D surface plot of TE[HTC] against TSU[LTC] on COP.REF[LTC]
(d) Interaction, (e) COP.REF[LTC] and (f) 3D surface plot of TE[HTC] against TSUB[LTC] on COP.REF[LTC]


G: M[HTC] (kg/s)
COP.REF[LTC]
B: TE[HTC] (0C)
G: M[HTC] (kg/s)
B: TE[HTC] (0C)
COP.REF[LTC]
G: M[HTC] (kg/s)
B: TE[HTC] (0C)

a b c



d e f

Figure 3.7: (a) Interaction, (b) COP.REF[LTC] and (c) 3D surface plot of TE[HTC] against M[HTC] on COP.REF[LTC]
(d) Interaction, (e) COP.REF[LTC] and (f) 3D surface plot of TCAS[DIFF] against TE[LTC] on COP.REF[LTC]

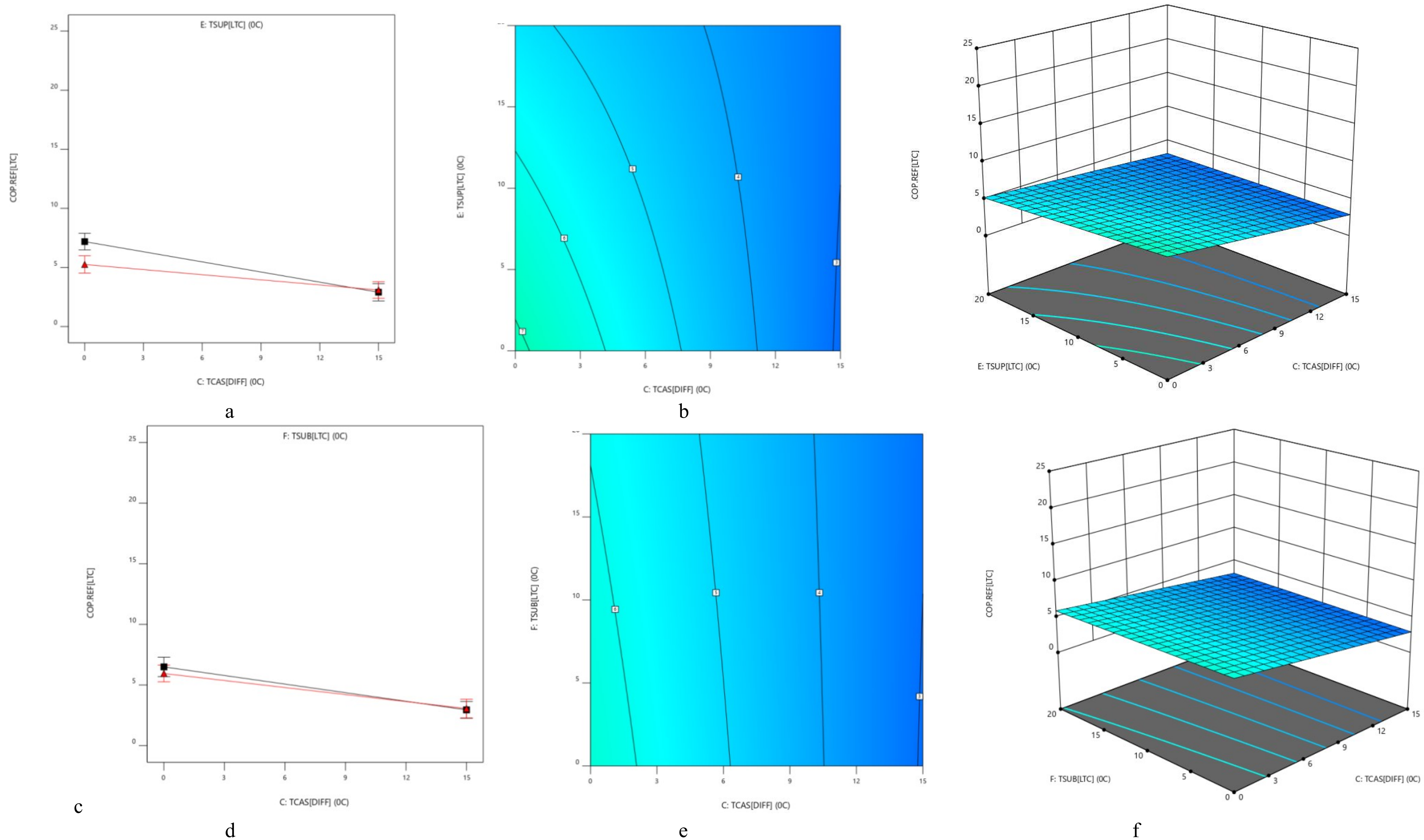


Figure 3.8: (a) Interaction, (b) COP.REF[LTC] and (c) 3D surface plot of TCA[DIFF] against TSUP[LTC] on COP.REF[LTC]
(d) Interaction, (e) COP.REF[LTC] and (f) 3D surface plot of TCAS[DIFF] against TSUB[LTC] on COP.REF[LTC]

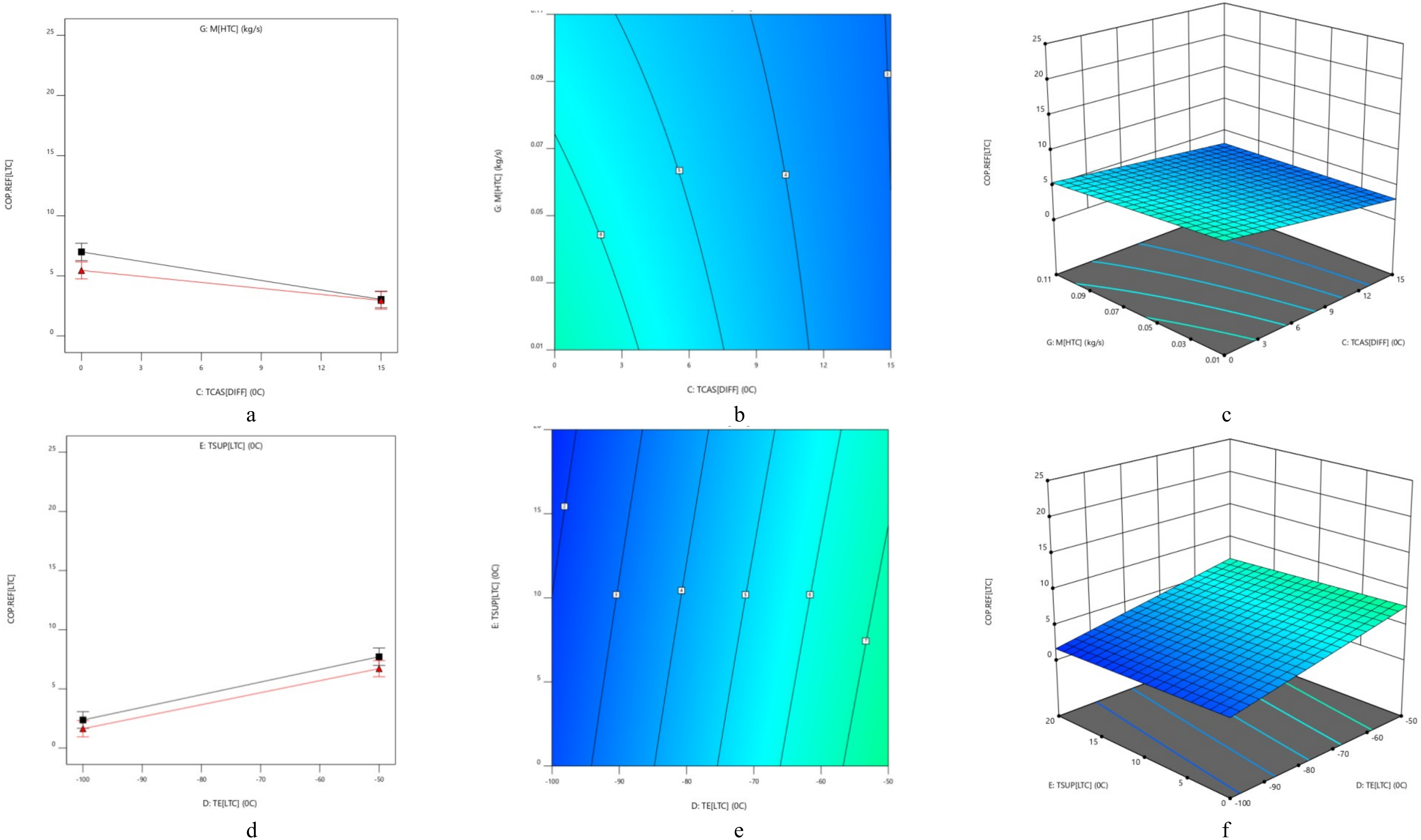


Figure 3.9: (a) Interaction, (b) COP.REF[LTC] and (c) 3D surface plot of TCAS[DIFF] against M[HTC] on COP.REF[LTC]
(d) Interaction, (e) COP.REF[LTC] and (f) 3D surface plot of TE[LTC] against TSUP[LTC] on COP.REF[LTC]

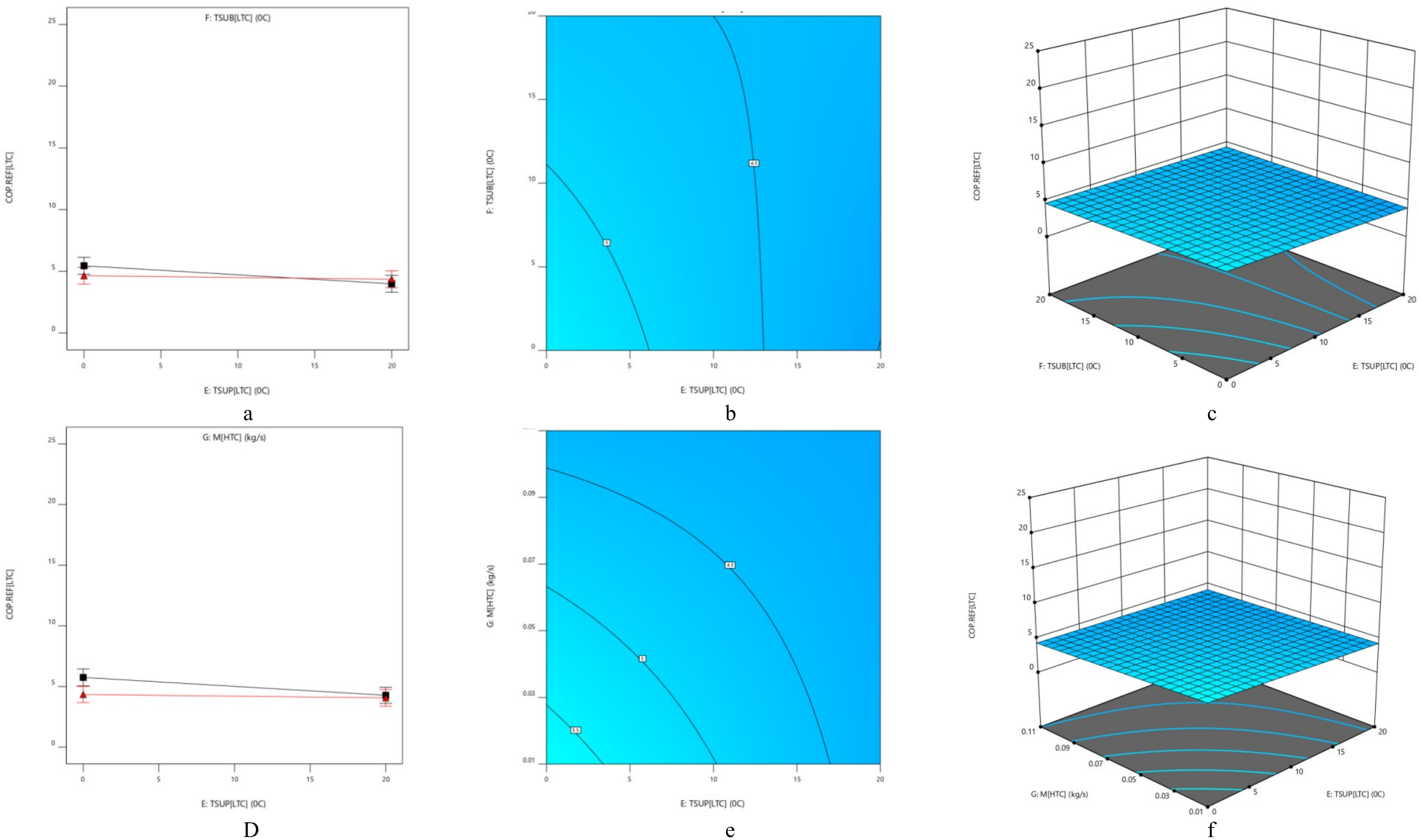


Figure 3.10: (a) Interaction, (b) COP.REF[LTC] and (c) 3D surface plot of TSUP[LTC] against TSUB[LTC] on COP.REF[LTC]
(d) Interaction, (e) COP.REF[LTC] and (f) 3D surface plot of TSU[LTC] against M[HTC] on COP.REF[LTC]

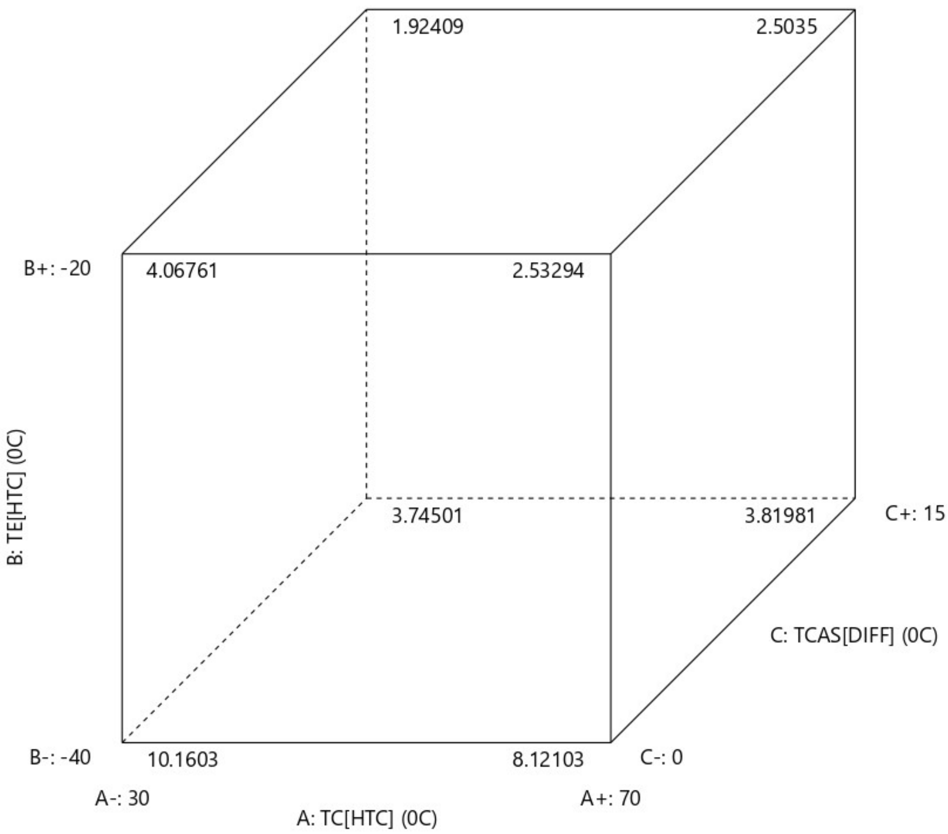


Figure 3.11: Cube Graph of Interaction of Important Factors on COP.REF[LTC]

3.3 Numerical Optimization Studies of COP.REF[LTC]

Numerical optimization of the data obtained for the COP.REF[LTC] value was conducted with the Design Expert Software (12.0.1). All the selected factors (Condensing Temperature ($T_{C,HTC}$), Evaporating Temperature ($T_{E,HTC}$), Cascade Temperature Difference ($\Delta T_{CAS,DIFF}$), Evaporating Temperature ($T_{E,LTC}$), Superheating Temperature ($T_{SUP,LTC}$), Sub-cooling Temperature ($T_{SUB,LTC}$), and Refrigerant Mass Flow Rate ($\dot{m}_{HTC}$)) were set to 'is in range' while COP[REF.SYST] value was set to 'maximize'.The numerical optimization selected was based on the highest desirability (Ogunsola*et al.,* 2022; Salman, 2014). In this study, the highest desirability was 0.691 while the optimum value suggested for TC[HTC], TE[HTC], TCAS[DIFF], TE[LTC], TSUP[LTC], TSUB[LTC], and ṁ[HTC] are 30 °C, -40 °C, 0 °C, -50°C, 0°C, 0 °C, and 0.11 kg/s, respectively (Fig. 3.12), compared to 30 °C, -40 °C, 0°C, -50°C, 0°C, 20 °C, and 0.01 kg/s, respectively, obtained from the experiment.

The numerical COP.REF[LTC] value is 18.085 while the measured (experimental) is 18.10. The percentage error difference between the numerical and experimental COP.REF[LTC] was 0.08%(Table 3.4), which indicated that no significant difference and level of acceptability of the experiment (Ogunsola*et al.,* 2022).

4 Conclusions

Half factorial design was a useful tool for the optimization of COP.REF[LTC] and the highest value of 18.1 of COP.REF[LTC] were obtained at optimum conditions of 30 $T_{C,HTC}$°C , -40 $T_{E,HTC}$°C, 0 $\Delta T_{CAS,DIFF}$°C, -50 $T_{E,LTC}$°C, 0 $T_{SUP,LTC}$°C, 20 $T_{SUB,LTC}$°C and 0.01 $\dot{m}_{HTC}$ kg/s. More research investigations into the optimization of workload of lower cycle (WC[LTC) and heat absorbed in the evaporator of lower cycle (QE[LTC] of the two-step refrigeration systems are suggested for further studies.

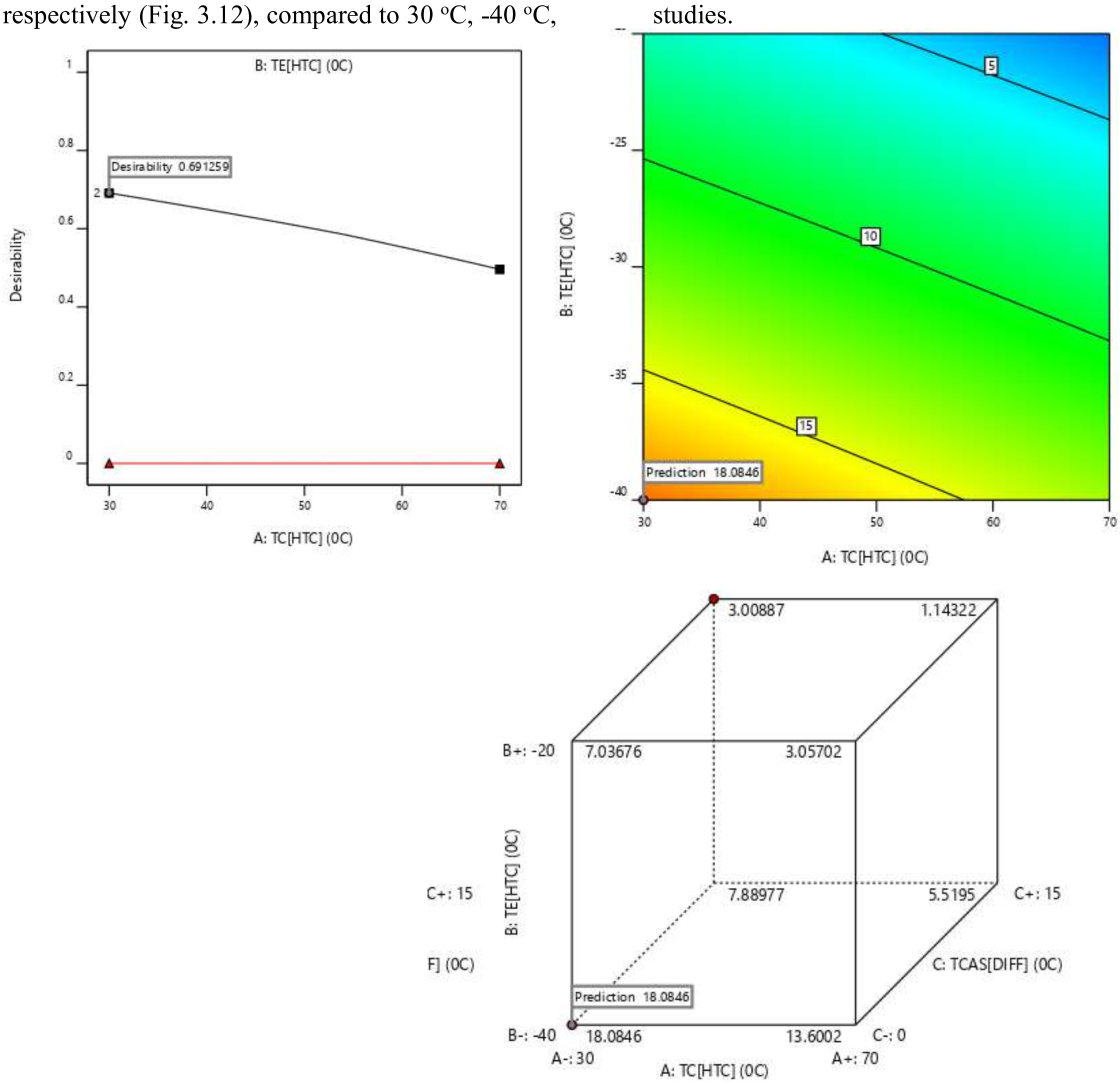


Figure 3.12: (a) Numerical interaction desirability, (b) Predicted desirability and (c) Cube graph of interaction of important factors on desirability

Table 3.4: Values of Experimental, Numerical Optimization and Percentage Difference

	A:TC[HTC] ºC	B:TE[HTC] ºC	C:TCAS [DIFF] ºC	D:TE[LTC]ºC	:TSUP[LTC]º C	F:TSUB [LTC] ºC	G:ṁ[HTC] kg/s	COP. REF. [LTC.]
Experimental	30	-40	0	-50	0	20	0.01	18.1
Numerical Optimization	30	-40	0	-50	0	0	0.11	18..085
% Different								0.08%

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