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Study on retaining natural refrigerant in seafood processing industries in India

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ABSTRACT

In the seafood processing sector in India, natural refrigerant such as NH_3 is currently replaced by Freon refrigerants such as HFC-404A, because these systems are comparably more compact, operate above atmospheric pressure and are less toxic. However, these synthetic refrigerants are one of the major sources of global warming. This paper focuses on a standalone-CO_2 system with a multi-ejector for transcritical operation and an NH_3-CO_2 cascade system considering the climatic conditions of important coastlines covering the majority of catch in India. The annual coefficient of performance is compared, and the results show that the COP of NH_3-CO_2 cascade system exceeds the HFC-404A system by 35 %. Cascade system performs better for -40 °C deep freezers, and the standalone-CO_2 system with heat recovery can be efficiently used for -18 °C cold storage. This study will aid in the retention of natural refrigerants in many seafood cities of India.

Keywords: ammonia, carbon dioxide, natural refrigerant, cascade, seafood processing.

1. INTRODUCTION

Seafood processing industries need various temperatures to maintain the quality of fish. The export of marine products from India stood at 1.39 million metric tons and was valued at USD 6.73 billion during 2018-19, with an impressive average annual growth rate of about 10 % in recent years (“NFBD,” 2023). After the fresh catch, fish will be stored in a refrigerated chamber or ice chamber in the fishing vessel. Thereafter, it will be transported for deep freezing and stored in cold storage. All this process requires intense refrigeration and energy consumption which contributes to carbon emissions. Traditionally ammonia is used as the refrigerant in these seafood processing industries. With the increase in residential areas around these industries, ammonia leakages are hazardous. Moreover, all ammonia systems are large and operate below atmospheric pressure for deep freezing. These natural refrigerant-based systems are slowly getting replaced by synthetic refrigerants having high GWP. India’s national determined contributions (NDCs) to phase out HFCs and restrict the global warming temperature to 2 °C, adopting CO_2 as a refrigerant and enhancing the existing refrigeration system in seafood industries have become significant.

Various research has been carried out on CO_2 cascade systems. For refrigerant pair NH_3-CO_2, where NH_3 and CO_2 is used in the high-temperature and low-temperature circuit respectively. Lee et al. (2006) and Getu and Bansal (2008) carried out thermodynamic analyses of NH_3-CO_2 cascade system and determined the optimal cascade condensing temperature for maximum COP, which depends on evaporating temperature, condensing temperature and cascade heat exchanger temperature difference. Alberto Dopazo et al. (2009) theoretically analysed a NH_3-CO_2 cascade system for a low-temperature application. They developed relevant diagrams and correlations to serve as guidelines for the design and optimization of a cascade system. Bingming et al. (2009) and Dopazo and Fernández-Seara (2011) experimentally investigated the performance of NH_3-CO_2 cascade system. The system was compared with two-stage NH_3 and single-stage NH_3 systems. They found that below -40 °C evaporator temperature, COP of the cascade system is superior to others. Yilmaz et al. (2018) conducted a parametric study on NH_3-CO_2 cascade system for different operating and ambient conditions. The maximum COP was found in the range of 1.23-2.37. Bellos and Tzivanidis (2019) conducted a comparative study of 18 different CO_2 cascade systems for yearly operation in weather conditions of Athen, Greece. The result showed that natural refrigerants such as NH_3, R290, R600 and R1270 are more appropriate choices according to the energy efficiency and total equivalent warming impact criteria. Saini et al. (2021) carried out a comparative analysis of three NH_3-CO_2 cascade system configurations for application in seafood processing for high ambient conditions. The application involved cooling demand in deep freezing and cold storage. For these improved configurations, they report a COP advantage of 11.5-20.3 % more than the conventional cascade system. Oliver (2020) proposed three fluid NH_3-glycol–CO_2 system to take advantage of already installed NH_3 equipment. It is recommended, in the case of low investment cost comprising in energy efficiency.

Many studies have been carried out for the transcritical standalone-CO_2 system, in which the heating load is considered along with the refrigeration load. Reinholdt and Madsen (2010) investigated heat recovery possibilities of transcritical CO_2 refrigeration systems for supermarket cold storage. They concluded that energy consumption for hot water production and flooring heating can be reduced drastically. Cecchinato et al. (2012) analysed different layouts for supermarket refrigeration systems. The energy efficiency of the system based on natural refrigerants was improved by optimizing the components and recovering the thermal energy for different climatic conditions. CO_2 was utilised as both heat transfer fluid and refrigerant. They reported annual energy savings higher than 15 % for the most efficient configuration with respect to the baseline system. Fricke (2014) investigated the energy consumption of a supermarket refrigeration using energyplus energy modelling tool. They found that the waste energy utilisation potential of a transcritical booster CO_2 system for application in desiccant regeneration, water heating and space heating was better than HFC-404A direct expansion system for 16 cities in the United States. Hafner et al. (2016) conducted a case study of an Italian supermarket equipped with a transcritical CO_2 ejector system. They reported energy saving between 15-30 % for high ambient temperature climates. Polzot et al. (2017) evaluated the energy performance of a CO_2 refrigeration system, which provides heating for domestic hot waters system and cooling for frozen food storage. They minimised annual electric energy consumption by 6.5 %.

This paper proposes an NH_3-CO_2 and NH_3-Hycool-CO_2 cascade refrigeration system for seafood processing operating in seafood cities along the western and eastern coastlines of India. India's coastline have high constant ambient temperature around 35 °C throughout the year. The performance of HFC-404A refrigeration system is compared with that of the cascade refrigeration system. Standalone-CO_2 multiejector refrigeration system is also proposed for fish cold storage, which recovers the heat rejected at high ambient temperatures for other process heating. The performance of these systems are analysed considering ambient temperatures of west and east coastline of India.

2. INDIAN COASTAL CLIMATE

The Indian coastline is covered by the Arabian Sea in the west and the Bay of Bengal in the east as shown in Figure 1. The coastline can be divided into western and eastern coastlines having major seafood processing cities. Veraval, Mumbai and Cochin in the west and Chennai, Vizag and Kolkata in the east. These cities experience tropical climates with warm and humid weather, nearly constant ambient temperature between 26-35 °C and relative humidity of 55 – 85 % throughout the year (“IMD,” 2023). The average high temperatures of seafood cities are shown in the table 1.

Table 1. Average high temperatures of important seafood cities in India

Month	Veraval		Mumbai		Cochin		Chennai		Vizag		Kolkata	
	Temp. (°C)	RH (%)	Temp. (°C)	RH (%)	Temp. (°C)	RH (%)	Temp. (°C)	RH (%)	Temp. (°C)	RH (%)	Temp. (°C)	RH (%)
1	29.2	57	30.2	62	31.9	61	29.3	67	29.5	63	25.8	61
2	29.8	63	30.3	62	32	65	30.9	66	31.6	62	29.2	54
3	31.7	72	31.7	63	32.6	68	32.9	67	34.2	63	33.5	51
4	32.1	76	32.9	66	33	70	34.5	70	35.4	67	35.3	62
5	32.6	77	34	68	32.4	73	37.1	68	36.3	68	35.3	68
6	32.5	80	32.2	77	30.3	82	37	63	35.4	67	33.8	77
7	30.8	84	29.9	85	29.6	83	35.3	65	33.4	71	32.4	82
8	29.9	85	29.9	84	29.5	82	34.7	66	33	73	32.2	83
9	31.1	80	30.6	80	30.2	79	34.2	71	33	76	32.4	82
10	33.9	72	33.1	72	30.7	77	32.1	76	32.3	73	32.2	75
11	33.4	63	33.8	65	31.3	72	29.9	76	30.9	66	30.1	67
12	30.8	59	32.2	63	31.9	64	28.9	71	29.5	63	27	65

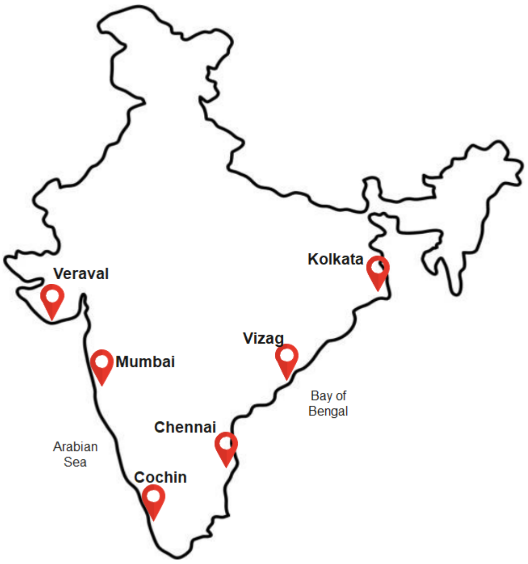

Figure 1: Important seafood cities location in India

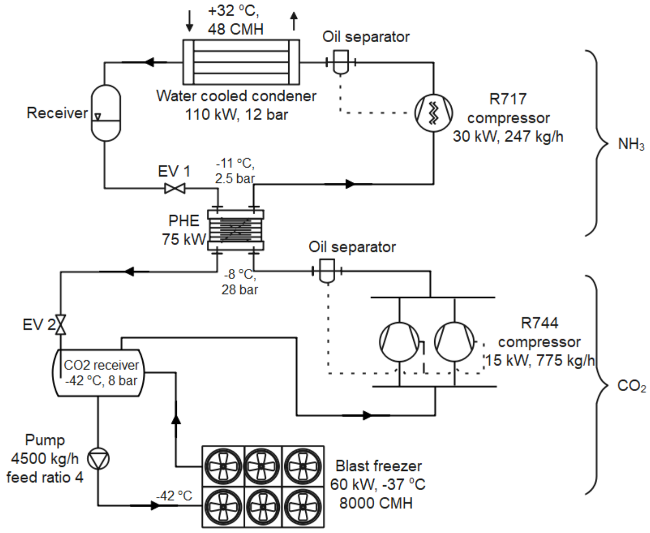

Figure 2: NH_3-CO_2 pumped cascade refrigeration system

3. DESCRIPTION OF INVESTIGATED SYSTEM

NH_3-CO_2 and NH_3-Hycool-CO_2 cascade freezers are investigated and compared with conventional HFC-404A freezer. Additionally, Standalone-CO_2 cold storage equipped with heat recovery for process heating is also studied. The systems are described as follows,

3.1. NH_3-CO_2 pumped refrigeration for blast freezer

Figure 2 shows the cascade refrigeration system selected for 60 kW cooling capacity. The cascade NH_3-CO_2 refrigeration unit is designed to operate a blast freezer at -42 °C. The refrigeration system works on the principle of the mechanical vapour compression refrigeration cycle. Anhydrous ammonia (R717) and CO_2 (R744) is used as refrigerant for high and low temperature refrigeration cycle respectively. The liquid CO_2 is pump fed to the blast freezer evaporator coils at the temperature -42 °C. Pumped CO_2 is implemented here, consisting of circulation vessel (Low pressure liquid receiver) semi-hermetic reciprocating compressors, individual oil separators and a cascade condenser. The high-temperature circuit has a water-cooled shell and tube condenser, a high-pressure receiver, a cascade heat exchanger, oil separator and a screw compressor. The low-temperature circuit transfers the heat to the high-temperature circuit through a cascade heat exchanger. The cascade heat exchanger can be a shell and tube or a flooded plate heat exchanger. Here a flooded plate heat exchanger is considered. The design pressure for the CO_2 cycle is 35 bar, equivalent to 0 °C CO_2 saturation temperature. The standing pressure of the CO_2 cycle is maintained below the design pressure by condensing the boil-off CO_2 vapour to the liquid phase using an auxiliary cooling unit with power backup. If there is an operational challenge in maintaining the CO_2 pressure well below the design pressure, the safety valves installed on the system will release the CO_2 gas pressure.

A PLC controller will continuously monitor and operate the various functions for the efficient and safe operation of both CO_2 and ammonia systems.

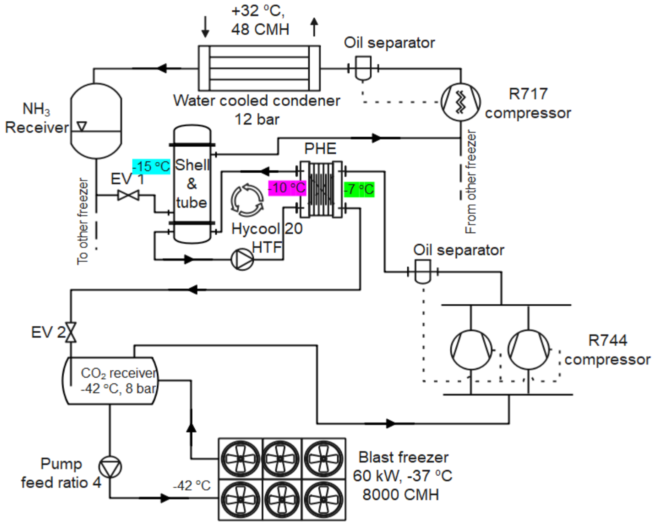

Figure 3: NH_3-Hycool-CO_2 cascade refrigeration system

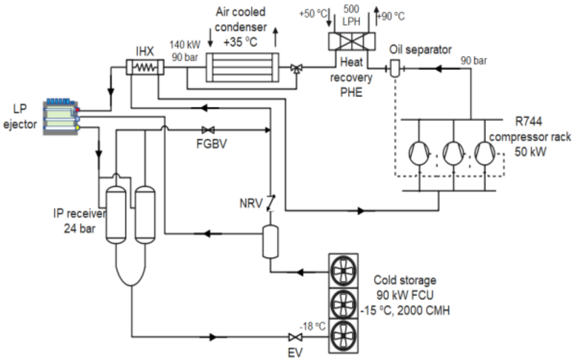

Figure 4: Transcritical CO_2 refrigeration system

3.2. NH_3-Hycool-CO_2 refrigeration for blast freezer

Figure 3 shows the three fluid cascade refrigeration system. The NH_3-Hycool-CO_2 cascade refrigeration unit is designed similarly to the system described in section 2.1, which will operate a blast freezer at -42 °C. All the components will remain the same except the cascade heat exchanger. The heat is exchanged through three fluids CO_2, Hycool and NH_3. In this case, two heat exchangers are required. Both of the heat exchangers can be plate heat exchangers or shell and tube heat exchangers. The advantage is that the heat exchanger need not be flooded. The cost-effective configuration is to have a shell and tube at the NH_3 side and a plate heat exchanger at the CO_2 side. The heat transfer fluid Hycool is circulated by a small capacity pump. The introduction of an additional heat exchanger, compared with a conventional NH_3-CO_2 cascade system, innately leads to a loss in energy efficiency. However, these systems can be adopted in cases where the existing NH_3 system could be modified to a cascade refrigeration system which will reduce the overall cost of the system. Also, the risk associated with modifications such as dry expansion, cascade heat exchanger leak leading to ammonia carbamate and the need for extra controllers to synchronize NH_3 and CO_2 compressor can be neglected.

3.3. Standalone-CO_2 system with heat recovery for cold storage

Figure 4 shows the standalone-CO_2 refrigeration system selected for 90 kW cooling capacity. The standalone-CO_2 refrigeration unit is designed to operate cold storage at -18 °C. The refrigeration system works on the principle of the mechanical vapour compression refrigeration cycle. CO_2 (R744) is used as a refrigerant throughout the system. Direct expansion (DX) at 18 °C is implemented here, consisting of an air-cooled condenser, intermediated liquid receiver, semi-hermetic reciprocating compressors, individual oil separators and heat recovery for processing heating. The design pressure for the CO_2 cycle is 160 bar at the high-pressure side, 100 bar at intermediate pressure and 60 bar at the low-pressure side. The standing pressure of the CO_2

is maintained below the design pressure at the lower side as cold storage is operating continuously. If there is an operational challenge in maintaining the CO_2 pressure well below the design pressure, the safety valves installed on the system will release the CO_2 gas pressure and can be refilled at a low-cost.

4. MODELLING

The thermodynamic model is developed using the equations solver tool EES®, from which the CO_2 and NH_3 properties can be directly obtained. For calculating realist performance, actual compressors were selected from BITZER and DORIN. The compressor behaviour polynomial equations were used to obtain cooling capacity, input power and mass flow rate. The operation is assumed to be in a steady state with no heat and pressure loss. In the NH_3-CO_2 cascade refrigeration system, a 5 °C approach temperature is considered for a high-temperature circuit condenser. The condensing temperatures of 30 to 40 °C for various evaporator temperatures of -40 °C, -45 °C, -50 °C , and the cascade heat exchanger temperature differences of 3 K, 5 K and 7 K is considered for parametric study. In a standalone-CO_2 refrigeration system, a condenser approach temperature of 3 °C with optimum gas cooler pressure, ejector efficiency of 30 %, internal heat exchanger efficiency of 30 % and medium temperature evaporator of 18 °C is considered. For comparison, a simple thermodynamic model for HFC-404A was developed. Ambient temperatures of different seafood cities were taken to evaluate the performance of both cascade, HFC-404A and standalone-CO_2 refrigeration systems throughout the year. Flow chart of the analytic simulation is presented in Figure 5.

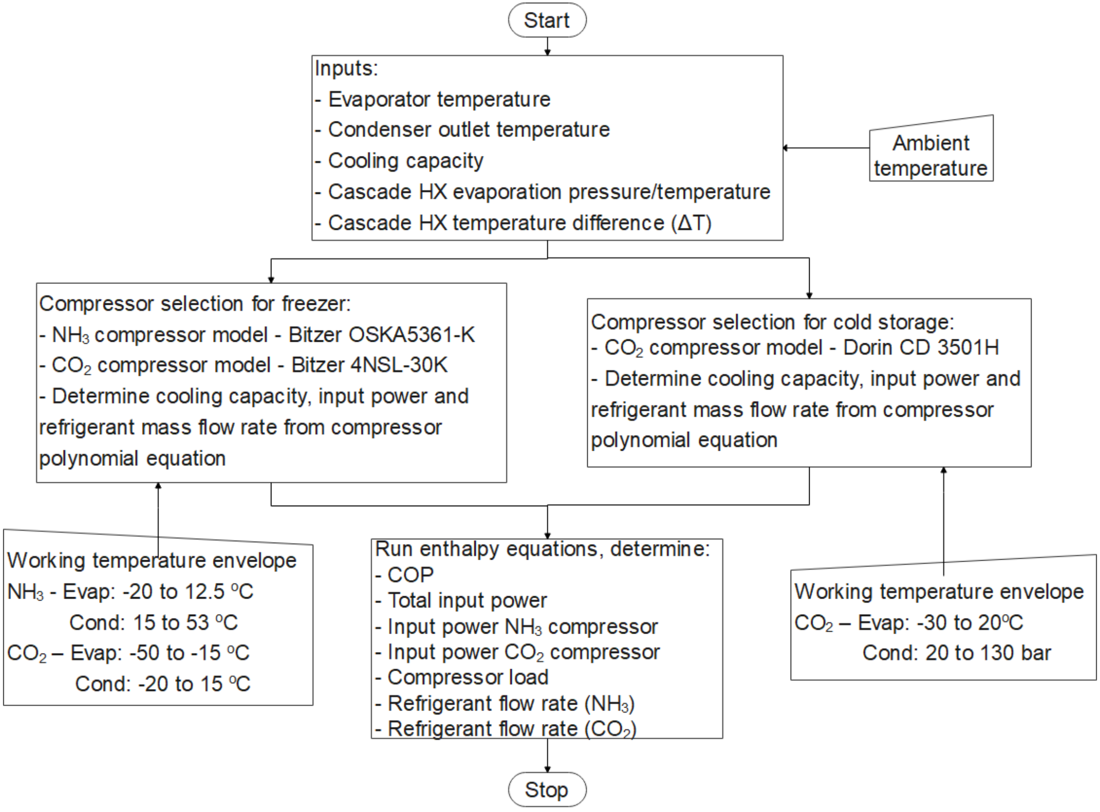

Figure 5: Flow chart for analytic simulation

4.1. Performance calculations

Coefficient of performance is the scale used to measure the performance of both deep freezer and cold storage refrigeration, which given by Eq. (1),

$$COP_{ref} = \frac{Q_E}{P} \qquad \text{Eq. (1)}$$

Where Q_E is the cooling capacity of evaporator (W) and P denotes the total input power (W) to all compressors. The heat recovery performance from standalone-CO_2 system can be measured using the heat pump COP equation which is given by Eq. (2),

$$COP_{hp} = \frac{Q_{HR}}{P} \quad \text{Eq. (2)}$$

Where Q_{HR} is the heat recovered (W) from the heat recovery unit.

The combined COP for cold storage is given by Eq. (3),

$$COP_{comb} = \frac{Q_E + Q_{HR}}{P} \quad \text{Eq. (3)}$$

5. RESULTS AND DISCUSSIONS

5.1. Parametric study of cascade refrigeration system

5.1.1. Effect of cascade heat exchanger evaporator pressure

For maximum COP in a cascade refrigeration system, there exists optimum condensing temperature, which depends on evaporator temperature T_E, cascade heat exchanger temperature differences $\mathbf{\Delta}T_{HX}$, and condenser outlet temperature T_C which is reported by (Lee et al., 2006), (Aghazadeh Dokandari et al., 2014) and (Saini et al., 2021). Accordingly, in a real system like deep freezers where the evaporator temperature is fixed, the cascade heat exchanger evaporating pressure needs to be evaluated initially. This depends on the selection of cascade heat exchanger and high-temperature side condenser such as shell and tube heat exchanger (high **Δ**T) or plate heat exchanger (low **Δ**T). The COP variation with respect to cascade evaporating pressure for various cascade heat exchanger temperature differences is shown in Figure 6. From Figure 6, it can be seen that COP reaches a peak value and then decreases with an increase in pressure. The overall temperature differences, namely the condenser approach temperature and cascade temperature differences, also plays a major role in selecting the required cascade evaporating pressure. The manufacturers can decide on the investment cost based on the availability and selection of both cascade and high-temperature side condensing heat exchanger. Heat exchangers with small **Δ**T will be expensive. It can be concluded that low-cost heat exchangers such as shell & tube could be used at the high-temperature side, and heat exchangers with high heat transfer coefficient such as plate heat exchanger can be used as the cascade heat exchanger.

5.1.2. Effect of condenser outlet temperature

Figure 7 shows the impact of different condensing temperatures on the performance at various evaporating temperatures T_E and various cascade heat exchanger temperature differences ΔT_{HX}. The figure shows that increasing condensing temperature reduces COP and is linearly related to the parameters of condenser outlet temperature, evaporator temperature and cascade heat exchanger temperature differences.

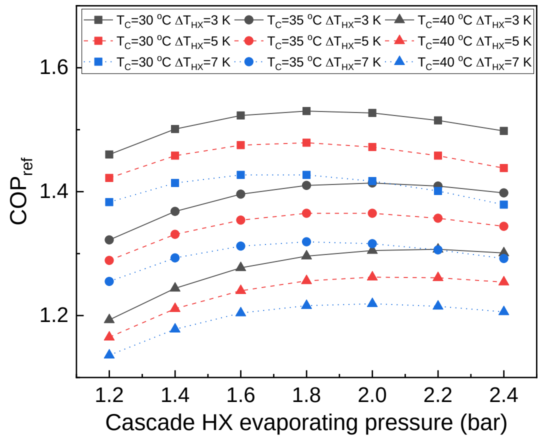

Figure 6: Performance variation with cascade evaporating pressure

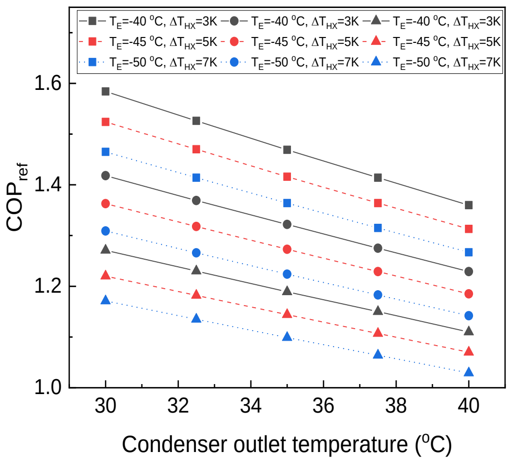

Figure 7: Performance variation with NH_3 condensing temperature

5.2. Year-around performance of cascade, HFC-404A and standalone-CO_2 refrigeration system

Figure 8a shows the COP variation of a NH_3-CO_2 cascade refrigeration system throughout the year for various seafood cities. The COP varies for an average range of 1.33–1.42 for the west coastline and an average range of 1.28–1.45 for the east coastline. Figure 8b shows the COP variation of a HFC-404A refrigeration system throughout the year for various seafood cities. The COP varies for an average range of 0.81–0.95 for the west coastline and an average range of 1.03–0.72 for the east coastline.

The performance of the cascade refrigeration system is higher than HFC-404A refrigeration system for the deep freezing application at -42 °C. The COP of the cascade refrigeration system exceeds the HFC-404A refrigeration system by an average of 35 %, as shown in the Figure 8c for all the major seafood cities in India.

To take advantage of already installed ammonia equipment, NH_3-Hycool-CO_2 cascade refrigeration system can be adopted. Figure 8d shows the efficiency loss in a three-fluid refrigeration system compared to a conventional cascade refrigeration system. From Figure 8d, it can be seen that COP percentage loss of 10-14% due to additional heat exchanger, which is an acceptable trade-off between efficiency and investment cost. Moreover, the COP is higher when compared to HFC-404A refrigeration system.

In the Standalone-CO_2 system for cold storage application at -18 °C evaporator temperature with heat recovery, the combined COP varies for an average range of 3.28-3.69 for the west coastline and an average range of 3.15-3.86 for the east coastline, as shown in Figure 8e

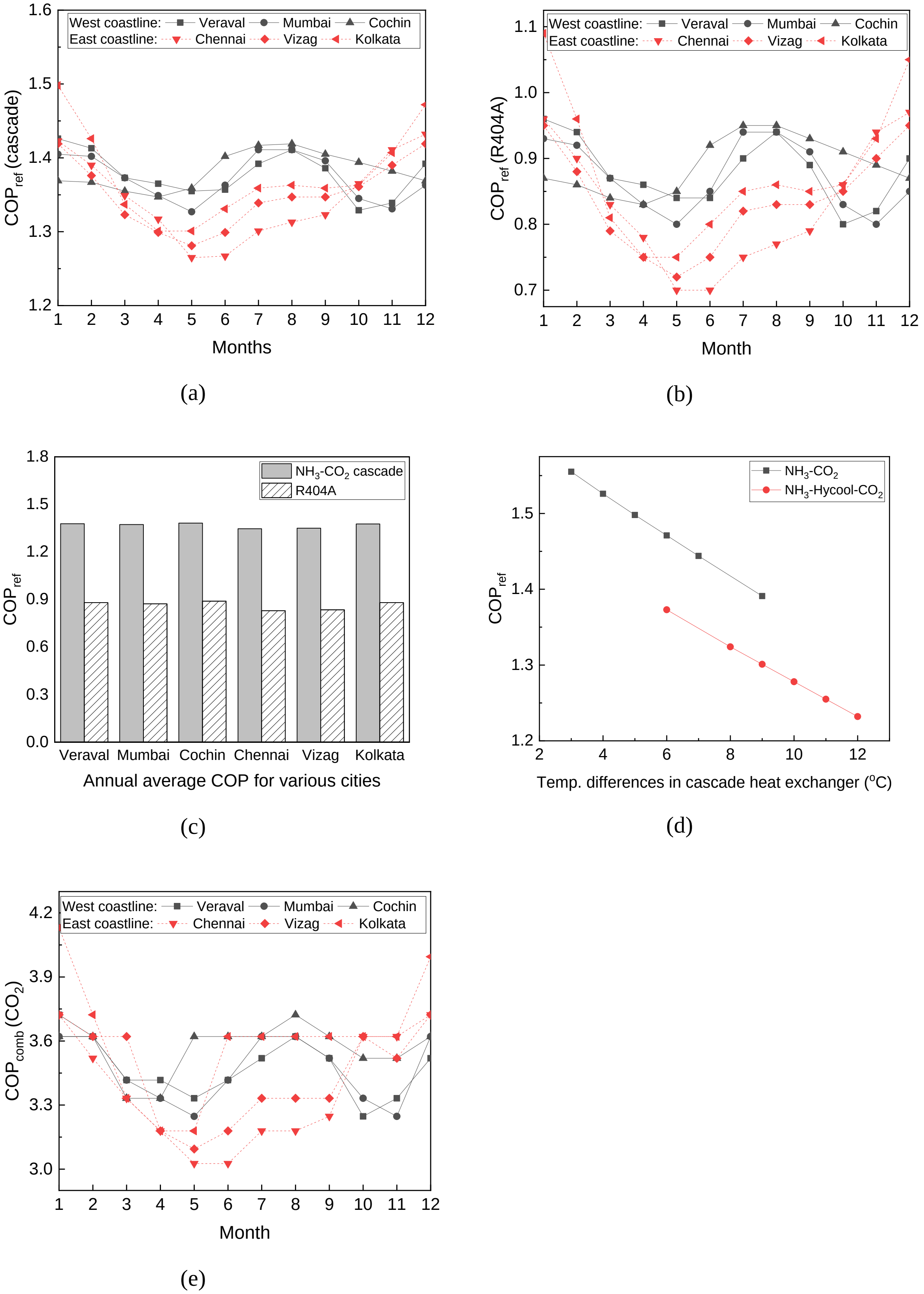

Figure 8: Performance variation (a) monthly COP of cascade (b) monthly COP of HFC-404A (c) annual average COP (d) COP comparison of two & three fluids (e) monthly COP of standalone-CO_2

6. CONCLUSION

The performance of cascade refrigeration systems using NH_3-CO_2 and NH_3-Hycool-CO_2 refrigerant pair for deep freezing applications for fish processing in various important seafood cities in India was investigated in this article. The performance were compared with the HFC-404A refrigeration system. The COP of the cascade refrigeration system exceeds the HFC-404A refrigeration system by an average of 35 %. The selection of components, mainly the cascade heat exchanger and high-temperature side condenser, play a vital role in increasing efficiency. Due to an additional heat exchanger in the three-fluid cascade refrigeration system, it is inherently susceptible to efficiency loss. However, the initial investment cost will be low. Further, a standalone-CO_2 refrigeration system with heat recovery is proposed for operation in the same ambient conditions. This system can be efficiently used for cold storage applications with an average COP value of 3.5. This study will aid to retention of natural refrigerants such as NH_3 and promotion of CO_2 for industrial application in high ambient temperatures existing in many seafood cities of India.

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NOMENCLATURE

T_C	condenser outlet temperature (°C)	hp	heat pump
Q_E	evaporator cooling capacity (W)	HX	heat exchanger
T_E	evaporator temperature (°C)	ref	refrigeration
Q_{HR}	heat recovery (W)		*Abbreviations*
P	input power (W)	COP	coefficient of performance
ΔT	temperature differences (K)	HFC	hydrofluorocarbon
	Subscript	RH	relative humidity
comb	combined		

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