PAPER ID: 0657
DOI: 10.18462/iir.compr.2024.0657

UPCOMING NATURAL REFRIGERANT-DRIVEN HEATING AND COOLING SYSTEMS IN INDIA

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ABSTRACT

India's heating, ventilation, air conditioning, and refrigeration (HVAC&R) industry still mainly employs synthetic refrigerants, exacerbating global warming. Promoting natural refrigerants may facilitate the transition to clean, sustainable heating and cooling options. However, in addition to the technical difficulties brought on by high ambient temperatures, non-technological impediments such as lack of expertise with the technology, general hesitance to new technology, and a shortage of appropriately experienced experts and installers hamper the adoption of the latest technologies. The Future Refrigeration India: INDEE+ project aims to increase confidence in the HVAC&R sector by implementing and demonstrating some natural refrigerant-driven heating and cooling systems. Ejector-supported 140 kW R744 systems is proposed for a hot water supply unit for a large school kitchen. The system is designed to meet both the heating and cooling loads simultaneously. The second investigation focuses on operating a 350 kW CO_2-NH_3 cascade freezer in a fish processing factory. The third unit under development is an on-board refrigeration system that produces ice from seawater using R290 (propane). This paper initially covers the modelling, simulation, and theoretical performance evaluation of the designed systems. Further validation of the models with data from the industrial areas is presented. The outcomes of this demonstration work in real industrial scenarios will serve as guidelines to assist the transition to more environmentally friendly heating and cooling systems in India.

Keywords: Natural Refrigerant, Carbon Dioxide, Ammonia, COP, Energy Efficiency

1. INTRODUCTION

The refrigeration sector is responsible for 10% of global greenhouse gas (GHG) emissions; further expansion in cooling services could result in an even significant increase in GHG emissions (Dong et al., 2021). Refrigeration and heat pump systems working on carbon dioxide is now widely used in countries with colder ambient temperatures. However, countries with warmer ambient temperatures are hesitant to adopt natural refrigerants, suspecting their energy efficiency and reliability. For instance, synthetic refrigerants are still primarily used in India's heating, ventilation, air conditioning, and refrigeration (HVAC&R) sectors, exacerbating global warming. Demonstration of natural refrigerants in some selected application domains could motivate designers, manufacturers, and end users to switch to clean heating and cooling choices in the future.

R744 is a non-flammable, non-toxic, readily available natural refrigerant that could mitigate global warming caused by the heating and cooling sector. However, the low critical temperature of R744 (about 31 °C) necessitates transcritical operating conditions in high ambient temperature countries, resulting in lower energy efficiencies than HFC-based systems (Gullo et al., 2018). Researchers have modified the standard R744 transcritical booster configuration in several methods like parallel compression, expansion work recovery through two-phase ejectors, and evaporators' overfeeding to enhance energy efficiency (Pardiñas et al., 2023). Also, the properties of R744 permit this unit to reject heat for heating purposes and could raise the temperature of sink fluid to about 90 °C. Such simultaneous heating and cooling solutions will be environmentally favorable and economically beneficial for sectors like buildings (hot water and room cooling) and industrial applications (boiler feed water preheating and space cooling). R744/R717 cascade configurations could be used where a standalone R744 system seems economically unviable, such as applications requiring lower temperatures without any simultaneous heating requirement. One such potential application is onshore seafood processing units where the fish received from fishing vessels are frozen, stored, and exported to the international market (Saini et al., 2021). In India, HFC-404A refrigeration systems or standalone two-stage R717 systems are mostly used in seafood processing units. As the temperature required for deep freezing is lower than 35 °C, when R717 alone is used, a subatmospheric pressure is needed in the evaporator, resulting in the possibility of air and moisture ingression. Also, most fish processing units are in densely populated seashore areas, and hence, there are regulations due to obnoxious odor and toxicity. Hence, a cascade refrigeration system with R744 on the low-temperature side and R717 on the high-temperature side could be an efficient and safe solution for Indian seafood processing units. Installation and performance evaluation of such systems in Indian conditions could also accelerate their adoption in countries with high ambient temperatures.

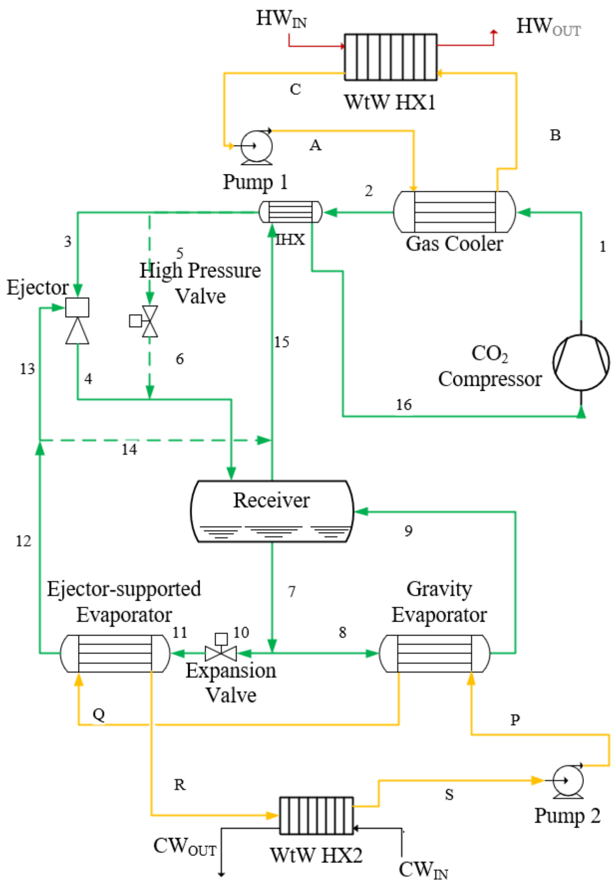
In addition to the technical difficulties posed by high ambient temperatures, non-technological impediments further complicate the process. These include a lack of expertise in the technology, a general hesitance to embrace new technology, and a shortage of appropriately experienced experts and installers. These challenges, while significant, can be overcome with the right approach and support. Future Refrigeration India: INDEE+ is an Indo-Norwegian project that aims to promote clean heating and cooling solutions for the future Indian HVAC&R industries. India's commitment to abide by its responsibilities to ratify the Kigali Amendment to the Montreal Protocol and the Paris Climate Agreement would be reinforced by the outcomes of INDEE+. To demonstrate the application of clean technology, an R744 heat pump/chiller unit for boiler feed water heating and space cooling, an R744/R717 cascade configuration in a seafood processing plant, and an R290 for onboard ice maker for fishing vessels are being installed and commissioned through INDEE+ project. This paper presents performance of these systems based on few week performance data obtained immediately after commissioning.

2. INDEE+ DEMONSTRATIONS SITES – SIGNIFICANCE AND DESIGN LAYOUT

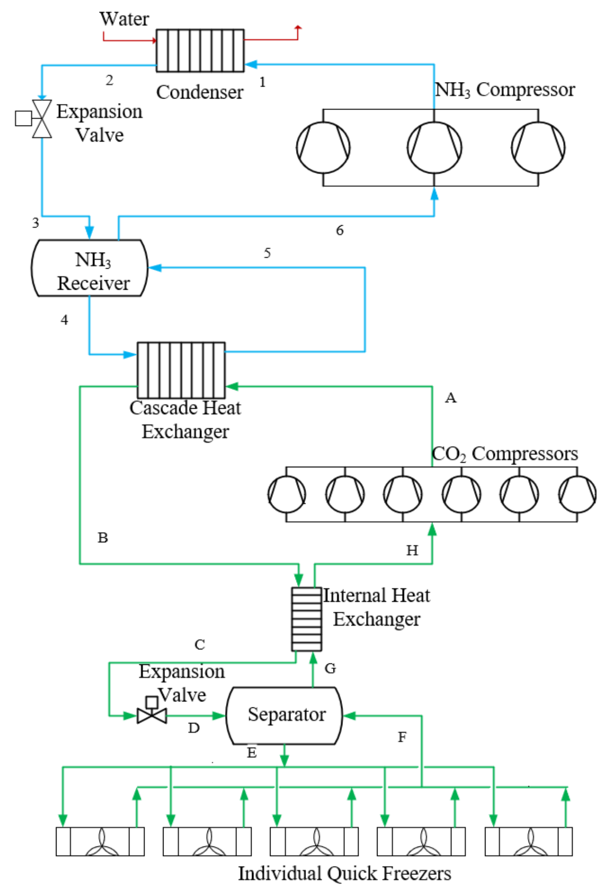
2.1. 140 kW transcritical R744 heat pump chiller for school kitchen

The Akshaya Patra Foundation is a not-for-profit organization headquartered in Bengaluru, India, that runs a mid-day meal program for school children. For food preparation, hot water was produced using an expensive diesel boiler. Through the INDEE+ project, an R744-based heat pump is being implemented to replace the boiler. The heat pump also produces chilled water for space cooling, such as air conditioning, in addition to hot water for cooking.

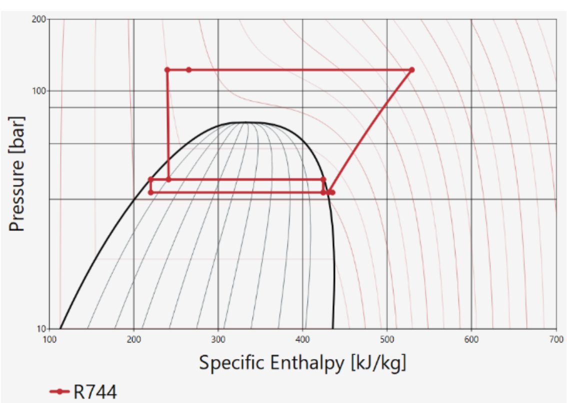
The transcritical R744 heat pump designed for a heating capacity of 140 kW and a cooling capacity of 102 kW is shown in Figure 1. The system comprises a compressor, three expansion valves, an ejector, two evaporators – one gravity fed and another ejector-supported, and an intermediate pressure (IP) receiver. The compressor compresses the R744 gas at its suction to high-pressure superheated gas, which passes through a gas cooler where heat is rejected to water, raising the water temperature to 90 °C. The heated water enters another water-to-water heat exchanger, where water to the kitchen boiler is heated from 24 °C to 87 °C. This two-level water heating arrangement is made to ensure the purity of the water used for cooking by avoiding direct contact with a gas cooler, which is a shell and tube-type heat exchanger made of cast iron susceptible to corrosion. The R744 stream exiting the gas cooler gets further cooled in an internal heat exchanger by a colder R744 stream flowing toward the compressor suction line. Further, the high-pressure R744 is expended in the expansion valve to an intermediate pressure, and the resultant two-phase mixture enters the receiver. The saturated liquid R744 from the bottom of the intermediate pressure receiver (IPR) flows to the gravity (MT) and ejector supported (LT) evaporators separately. The R744 circulates to the MT evaporator on the principle of a thermosiphon loop, while R744 enters the LT evaporator at a colder temperature after getting expanded across the expansion valve. The R744 stream leaving evaporates returns to IPR and further goes to compressor suction via IHX. The two evaporators cool water from 13 °C to 4 °C in two steps. Through a water-to-water heat exchanger on the cold side of the system, chilled water at 7 °C is produced, which is used for space cooling applications.



(a) Process flow diagram of R744 heat pump

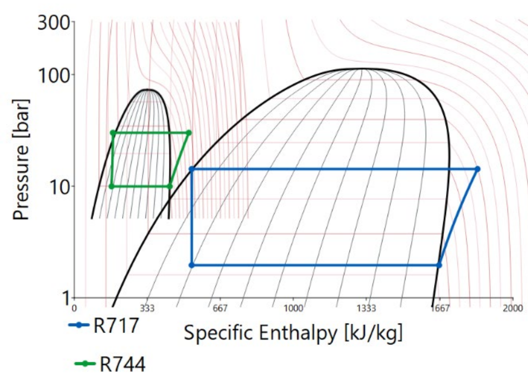


(a) Process flow diagram of R744/R717 cascade system



(b) p-h chart of R744 heat pump

Figure 1: Process flow diagram and p-h representation of R744 heat pump for school kitchen (direct expansion mode).



(b) p-h chart of R744/R717 cascade system

Figure 2: Process flow diagram and p-h representation of R744/R717 cascade systems for seafood processing.

2.2. 350 kW R744/R717 cascade systems for seafood processing

A 350 kW R744/R717 cascade unit has been built, installed, and commissioned recently at NAS Fisheries Pvt. Ltd. in Kochi is another INDEE+ demonstration site. It is a seafood processing facility with a tunnel freezer, and it requires an evaporation temperature of -40 °C to freeze cuttlefish and prawns. As shown in Figure 2, a cascade process heat exchanger (PHE) connects the R744-driven low-temperature circuit (LTC) and R717-driven high-temperature circuit (HTC). Both circuits work on the well-known vapour compression refrigeration cycle principles. LTC has six semi-hermetic Bitzer compressors, one of which is frequency-driven, an internal heat exchanger, an intermediate pressure receiver, a low-pressure receiver, and five individual quick freezers (IQF). R744 is condensed by R717 that circulates in HTC through a cascade plate heat exchanger (PHE). Three Bitzer R717 screw compressors, an oil separator, a high-pressure receiver, a water-cooled plate heat exchanger condenser, and an oil separator make up the high-temperature R717 circuit.

2.3. 30 kW R290 on-board ice maker for fishing boats

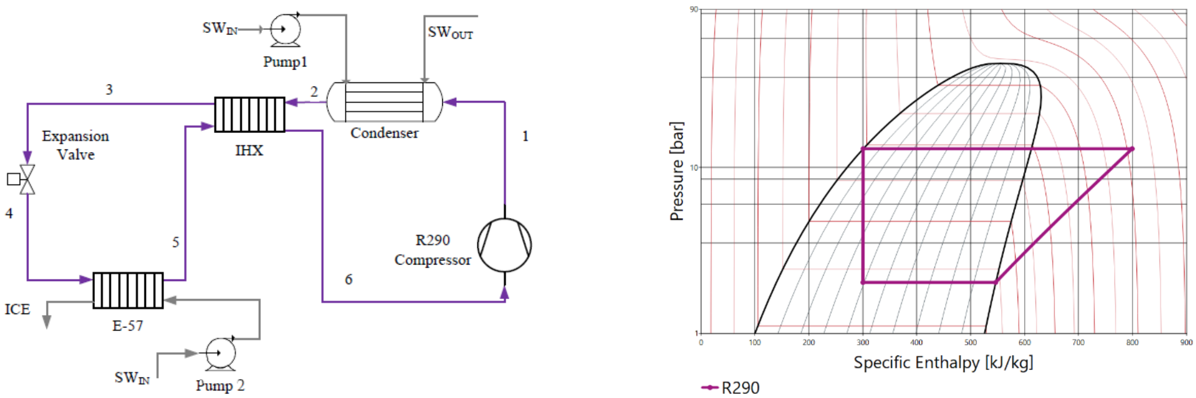


Figure 3: Process flow diagram and p-h representation R290 on-board ice maker for fishing boats.

To secure food quality, lower greenhouse gas emissions, and build a food value chain that is resilient to the future, there is a need for improvement in the active cooling system on small and medium-sized fishing vessels in India. Onboard ice production is the standard practice among trawlers worldwide and is considered conducive to food quality assurance and enhanced tractability. Figure 3 displays the schematic and corresponding p-h diagram for the proposed 30 kW propane refrigeration system that creates ice on board. An open-type screw compressor is meant to power the refrigeration system, which is directly linked to the boat engine via belt drive. An internal heat exchanger (IHX) superheats the vapor transported to the compressor suction while the refrigerant at the condenser output is subcooled. The evaporator is a plate freezer that creates ice block.

The refrigeration system for onboard ice production is in the design phase. For the same system, feasibility of an onboard refrigerated seawater system to produce ice on small-size fishing vessels has been investigated (Köster et al., 2024). The primary difficulty discovered is that heat transfer becomes much less effective as ice thickness increases, making it difficult to keep the compressor inlet sufficiently superheated. Performance of R290 to R404A and R407A has also been compared and found that the higher enthalpy of vaporization of R290 reduces the mass flow rate required for providing 30 kW cooling at -25 °C which leads to lesser compressor work and higher COP (Singha et al., 2024). However, further investigation is needed to size the condenser and internal heat exchangers. Since the unit has to be placed in a small fishing vessel, the size of the condenser needs to be minimized, and the internal heat exchanger should ensure sufficient heat at the compressor inlet.

3. PERFORMANCE OF INDEE+ NATURAL REFRIGERATION SYSTEMS

3.1 140 kW transcritical R744 heat pump chiller for school kitchen

A geometry-based model of the school kitchen heat pump chiller was developed considering only the direct expansion mode and a study on part load operation and operation at off-design temperatures was conducted (Bless et al., 2024). In this paper, the model has been extended to cover the ejector mode and a comparison of the part load operation in direct expansion and ejector mode is presented showing the major differences on the loads and coefficients of performances. The ejector model establishes an effective driving flow area and a linear relationship between the pressure increase and the suction mass flow rate. A PI-controller adjusts the nozzle's effective driving flow area to maintain the gas cooler pressure at 122.6 bar. The mass flow rate at the driving port is determined using Brennen's flow correlation for CO_2. Models for other components and simulation conditions remains same as Bless et al., 2024. The superheat after the ejector supported evaporator is set as 0.001 K since the evaporator is flooded. The superheat is controlled via the expansion valve after the receiver. As a simulation tool, Dymola has been used, including the TIL library from TLK-Thermo for modelling the system. The heat sink and source cycle are simulated with open boundaries since no data of load profiles are available. To simulate part-load operations, the cooling load was varied according to the compressor operation range for frequencies between 30 Hz to 55 Hz. The hot water outlet temperature is kept constant at 90°C by varying its mass flow rate.

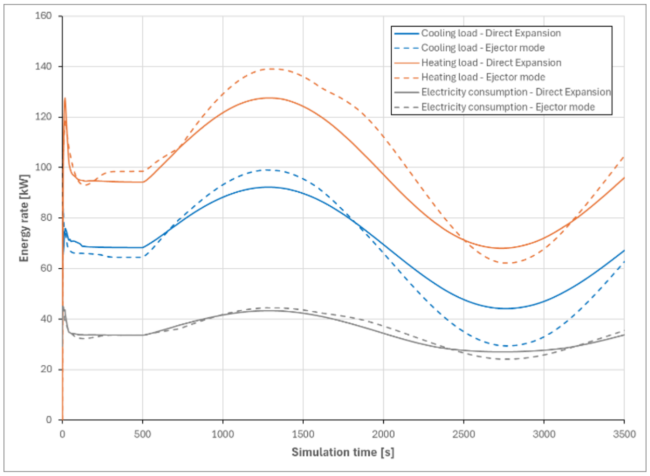


Figure 4: The heating, cooling and electrical power simulated with varying loads for the direct expansion and ejector mode.

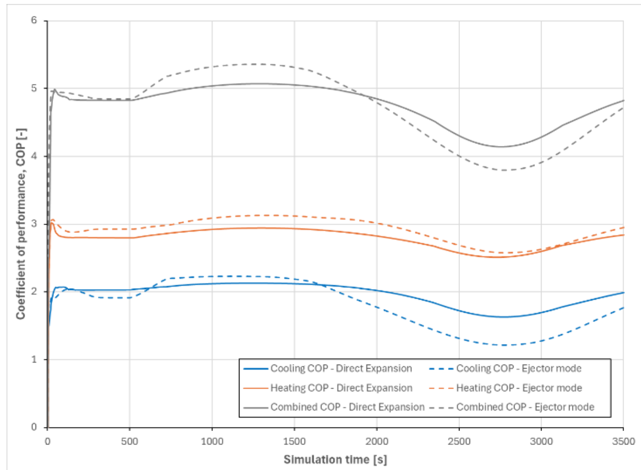


Figure 5: The heating, cooling and combined COP simulated with varying loads for the direct expansion and ejector mode.

From Figures 4 and 5, it may be observed that the curves for the loads and power are following the profile of the mass flow of this chilled water which is the model input in the shape of a sine curve. For the ejector mode, a maximum combined COP of 5.4 was achieved, corresponding to an increase of 6% towards the direct expansion mode. At minimum load, the pressure lift by the ejector (Figure 6) is lower and hence the direct expansion mode achieves higher COPs. From Table 1, it can further be concluded that the ejector mode offers a wider capacity range than the direct expansion mode.

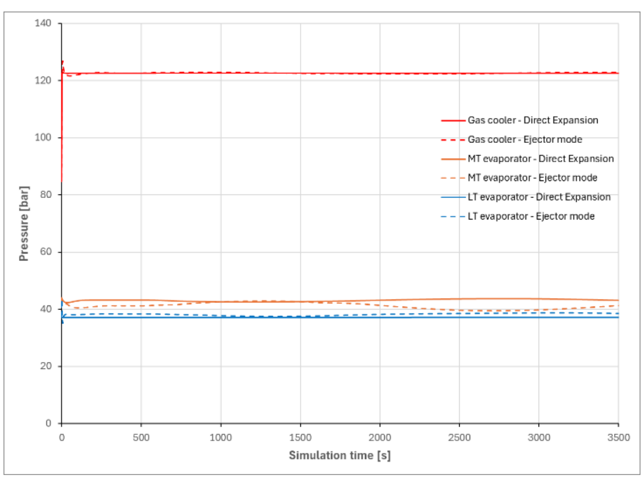


Figure 6: Variation of operating parameters of cascade system recorded for continuous 33 hours.

Table 1: Comparison at maximum and minimum load

Operation mode	Load	Heating capacity (kW)	Cooling capacity (kW)
Ejector mode	Maximum	62.3	29.3
	Minimum	139.1	99.0
Direct Expansion mode	Maximum	68.0	44.1
	Minimum	127.6	92.2

Operation mode	Load	Heating COP	Cooling COP
Ejector mode	Maximum	2.6	1.2
	Minimum	3.1	2.2
Direct Expansion mode	Maximum	2.5	1.6
	Minimum	2.9	2.1

3.2. 350 kW R744/R717 cascade systems for seafood processing

The performance of R744/R717 cascade system is evaluated in terms of coefficient of performance (COP), given as:

$$COP = \frac{\dot{Q}_c}{\dot{W}_{R744} + \dot{W}_{R717}} \qquad \text{Eq. (1)}$$

where $\dot{Q}_C$ is the heat rejected in the condenser (kW), $\dot{W}_{R744}$ is the power (kW) consumed by R744 compressor and $\dot{W}_{R717}$ is the power (kW) consumed by R717 compressor.

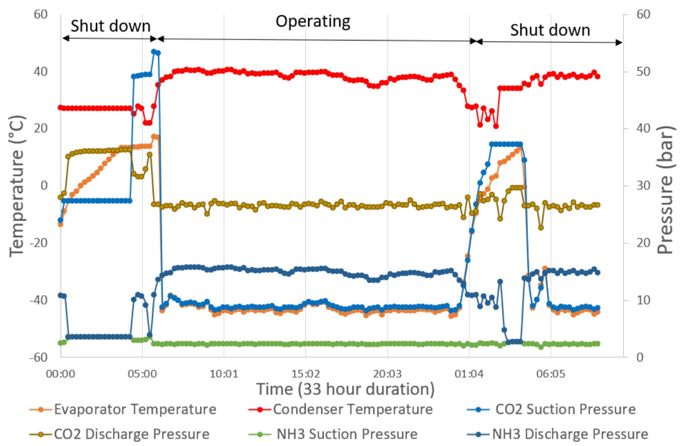


Figure 7: Variation of operating parameters of cascade system recorded for continuous 33 hours.

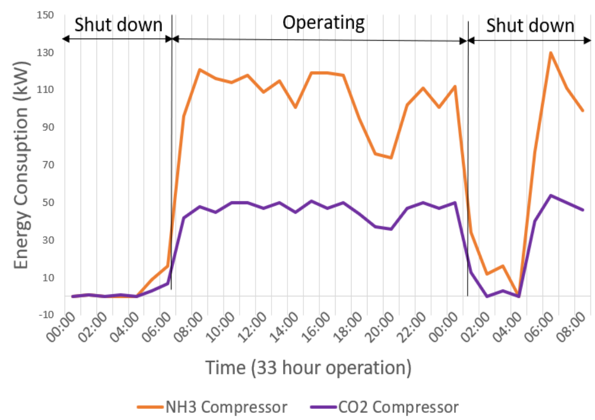


Figure 8: Variation of energy consumption by compressors of cascade system recorded for continuous 33 hours.

Figure 7 shows the variation of evaporator temperature, condenser temperature, suction and discharge pressures of both R744 and R717 compressors, recorded for 33 hours starting from midnight of June 2. The cascade system attained the designed temperature levels quickly from the shutdown conditions. During operation, the evaporator temperature varied between -41 to -44 °C, as the load (fish quantity) varied between 500 to 600 kg/hr in the tunnel freezer. The condenser outlet temperature ranged between 37 to 41 °C for a cooling water inlet temperature of 33 °C. The pressure ratio of the R744 compressor has remained constant at 3, while that of the R717 compressor varied between 6.5 and 7.0. Figure 8 shows the variation of power consumption of R744 and R717 compressors for the same duration of data recording as Figure 4. During the freezing operations, R744 and R717 compressors consumed 46.7 kW and 107.1 kW power respectively.

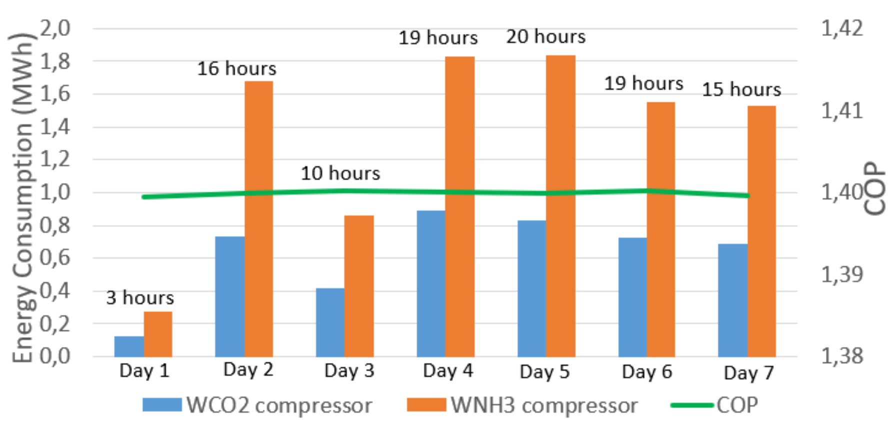


Figure 9: Performance of R744/R717 cascade refrigeration system considering 7 days of operation.

Figure 9 shows the accumulated energy consumption of R744 and R717 compressors and COP of the cascade refrigeration system for seven days, considering only operating hours. R717 compressors consume 68% to 70% of total energy consumption. Even though day 4 and day 6 had the same load and operating hours, an additional energy of 450 kWh was consumed for the parasitic load after freezer defrosting on day 3. The cascade refrigeration system achieved a COP of 1.40 with an evaporating temperature of about -42 °C. This COP is higher than the COP reported (in the range of 1.09-1.2) for a two-stage R717 system operating with an evaporating temperature of -38 °C (Bureau of Energy Efficiency, 2016). Therefore, it can be concluded that R744/R717 cascade systems have the potential to freeze at lower evaporating temperatures (below -40 °C) while delivering higher COP, consequently improving energy efficiency and size reduction and avoiding R717 away from food premises.

3.3. 30 kW R290 on-board ice maker for fishing boats

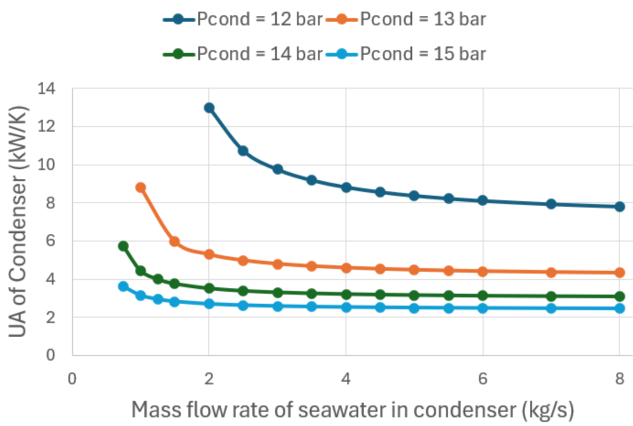


Figure 10: Effect of flow rate of seawater on UA

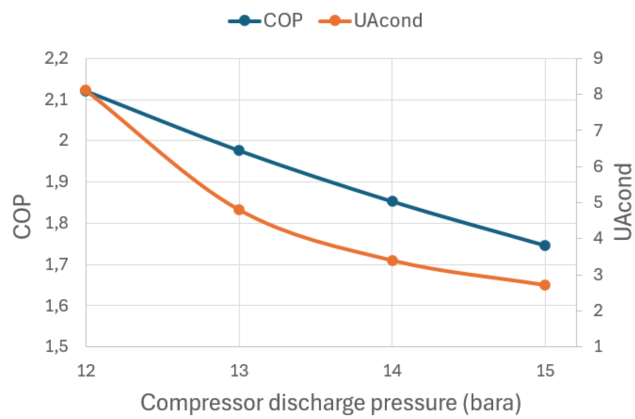


Figure 11. Best UA_{cond} values and respective COP

Figure 10 shows the effect of variation in the mass flow rate of seawater on the thermal size (UA) of heat exchangers at different compressor discharge pressures. The condition of R290 at the condenser outlet is fixed at the saturated liquid condition of all simulation cases. For a given mass flow of 2 kg/s, when compressor discharge pressure is increased by 1 bar from 12 bar, the UA of the condenser reduces by 61.6%. For a given compressor discharge pressure, there is a minimum threshold mass flow rate of water, beyond which the size of the condenser needs to increase exponentially to ensure complete condensation of R290 at its outlet. Increasing mass flow rate beyond this threshold value does not impact performance other than increasing sea water pump power. Figure 11 shows that this threshold value of mass flow rate decreases with an increase in compressor discharge pressure, decreasing the COP of the system. Therefore, a thermoeconomic optimization may help to arrive at an optimum UA of the condenser.

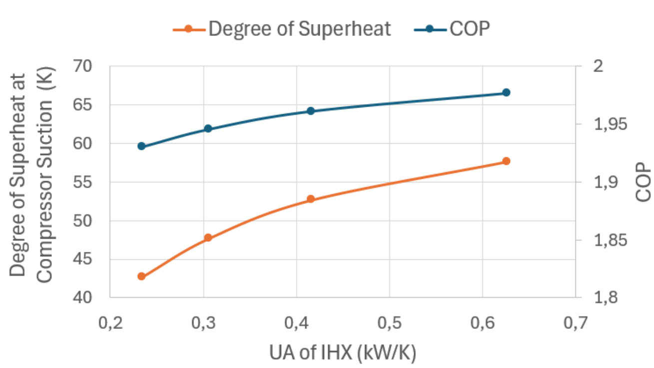


Figure 12: Effect of UA of IHX on COP and degree of superheat at compressor suction.

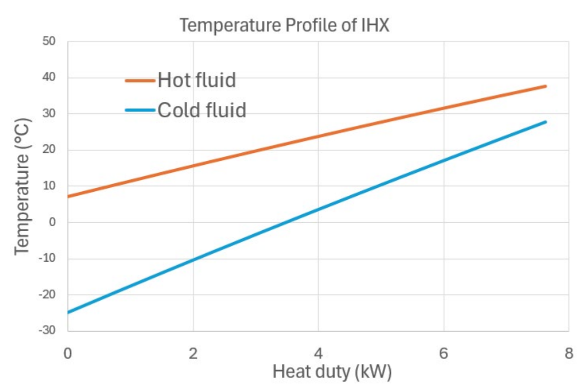


Figure 13. Temperature profile of IHX.

Figures 12 and 13 show that sufficient superheat at compressor suction could be ensured by having an internal heat exchanger (also known as liquid suction heat exchanger). Figure 9 shows that the IHX could be made as large as possible to have a temperature approach of 5 K or less so that the evaporator outlet temperature of -25 °C could be lifted to 32 °C and so that sufficient superheat will be maintained when ice thickness increases. Also, a higher size of IHX provides higher COP for the system. Figure 13 shows that though the mass flow rate of hot and cold fluids of IHX is the same, due to specific heat variations with temperature, the minimum temperature approach occurs at the warm end of IHX, which is in favor of the design requirements.

4. CONCLUSIONS

This paper presents a performance evaluation of three natural refrigerant systems, a promising step towards the future of clean cooling technology in India. With technical support from the Future Refrigeration India: INDEE+' project team, local vendors installed demonstration units working on natural refrigerants on different Indian industrial premises. After the commissioning, the operation and performance of these refrigeration/heat pump units are monitored. Simulation results of heat pump chiller unit for school kitchen ensures higher performance in ejector mode. The first set of data from the R744/R717 cascade system for seafood processing units shows the unit has seamlessly functioned below -40 °C with an average COP of 1.40. The paper also shows the design of a 30kW R290-based refrigeration unit in small fishing vessels to produce ice blocks for fish preservation. The project's outcome is to facilitate acceptance of similar natural refrigerant-driven systems and build competence for developing clean cooling technology among researchers, vendors, and end-users in India.

ACKNOWLEDGEMENTS

The authors acknowledge the support received from the ongoing Indo-Norwegian project 'Future Refrigeration India: INDEE+' funded by the Norwegian Ministry of Foreign Affairs.

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