Final Report

Demonstration of a $\text{CO}_2$ commercial refrigeration system in Jordan

by

Prof. Dr. -Ing Armin Hafner
Executive Summary:

As part of the Climate and Clean Air Coalition’s (CCAC) initiative on the proportion of hydrofluorocarbon (HFC) alternative technologies and standards, the project demonstrated the feasibility of a CO\textsubscript{2} transcritical system as a non-HFC based alternative to HCFC-22 in retail applications in countries with high ambient temperature though the full-scale replacement of an existing installation in Jordan.

The converted supermarket is located in the capital city of Jordan, Amman. It is the Middle East’s first transcritical CO\textsubscript{2} system in the food retail sector, commissioned in January 2018 at the Al-Salam military supermarket.

The annual electricity demand for the refrigeration unit is reduced by 40,000 kWh, which corresponds to a CO\textsubscript{2} emission reduction of approximately 32 metric tons.

The previously direct emissions related to refrigerant leakage are eliminated and correspond to an annual equivalent CO\textsubscript{2} emission reduction of approximately 35 metric tons.

Food wastage from the supermarket is now completely avoided, due to the stable operation of the CO\textsubscript{2} refrigeration unit.

During the first 20 months of operation, so far, no maintenance costs appeared. The annual saving for the supermarket owner is approximately 20,000 $.

The involvement of local companies, showing a real interest to further improve the know-how of the employees and demonstrating the willingness to learn is a key success factor for these kind of demonstration projects.
Project Overview

Broader context

Food losses in developing countries reach 40% throughout the supply chain, from initial agricultural production down to final household consumption. Reliable refrigeration systems can dramatically reduce food losses by keeping the food cold along its supply chain, thus establishing a ‘cold chain’. The establishment of a cold chain also enables farmers to demand higher prices for their products, since their sales are evened out instead of taking place at a time of oversupply in the market, and generate higher income. Cold chains are thus important links in moving closer to a circular economy in the food chain. However, the cold chain itself needs to be as green as possible, minimizing climate impact and following green design principles. New refrigeration technologies that eliminate the use of greenhouse gases, optimize energy consumption and reduce the need for maintenance and repair can help towards this aim. In countries with particularly high ambient temperatures, such as Jordan, there is a need for resource efficient refrigeration for cold chain service providers.

Main Approach

With funding from the Climate and Clean Air Coalition (CCAC), UNIDO has addressed this issue by piloting innovative, climate-friendly refrigeration at the Al Salam supermarket in Amman, Jordan. The project was implemented in collaboration with the Ministry of Environment of Jordan, along with national and international technology providers. Through the full-scale replacement of the supermarket’s existing installation, it demonstrated the feasibility of a CO$_2$ transcritical system in retail refrigeration in a high ambient temperature (HAT) country. Support encompassed the transfer of technology, which included greening the design and installing the new units, as well as the provision of equipment, such as display cabinets and compressors. The cabinets were made available through the involvement of local industry. Essential safety and maintenance training for local technicians and engineers at the supermarket was also provided. In order to promote the broad applicability of these technologies and the project results, information was disseminated through awareness-raising activities.
Technical summary

The aim of the project is to demonstrate the feasibility and monitor efficiency results of systems with CO$_2$ as the working fluid and as an alternative to HCFC-22 in retail installations that are still often used in many developing countries. The installed system is a CO$_2$ transcritical booster system with parallel compression. To ensure high efficiency also during the high ambient temperatures in the summer months, the system integrates state-of-the-art ejector technology. The system features non-superheated evaporator technology for both chilled and frozen food cabinets and storage rooms. The waste heat from the system can be recovered for hot sanitary water supply which saves further energy overall.

The net capacity on the medium temperature side accounts for 31 kW and the gross capacity 69 kW at -2°C. The low temperature capacity amounts to 38 kW at -25°C. The technology supplier of the project is Abdin Industrial, a 100 per cent Jordanian family-owned company, which provided the four and five door cabinets, set up all piping and finalized the on-site installation. The company worked closely with Italian-based international system manufacturer Enex who supplied the refrigeration system.

Results and Impact

This is the Middle East’s very first transcritical CO$_2$ refrigeration system in a supermarket, demonstrating green state-of-the-art technology within the cold chain. Results show that the system is delivering on energy savings, zero food loss and no maintenance costs in the first year of operation. The green design recovers waste heat from the system to supply sanitary hot water, further increasing the system’s energy efficiency. Trained local engineers and technicians have led to better servicing and maintenance and will also extend the system’s lifetime. The project successfully tested and validated technology that uses more climate-friendly alternative refrigerants in challenging conditions. This demonstrates that, within the cold chain, emissions of harmful substances can be reduced, thus minimizing environmental impact. The system’s success has established a better understanding of the applicability of the technology in countries with high ambient temperatures, and promoted innovation within the national industry, which is encouraging follow up projects in the region.
Facts & Figures

- 5 trainers/facilitators trained
- 30 technicians trained
- 30+ green jobs secured/created
- $500,000 worth of equipment/technology transferred
- 20-30% energy savings
- 10 regional and international workshops and conferences carried out, case study & results presented at 20 national and international events
- 10,000 people reached regionally and internationally through events and publications
- Zero in-store food waste and zero maintenance costs for the first year of operation
- Replacing harmful refrigerants
- Waste-to-energy
- Reducing resource consumption

System Set-up

![Diagram](image.png)

*Figure 1. Previous configuration with several HCFC 22 condensing units*
Figure 2. After implementation of the CO₂ refrigeration unit and refurbishment, i.e. increasing the number of both frozen and chilled display cabinets.

Refrigeration system configuration

The refrigeration system is an ejector supported CO₂ booster system with parallel compression and direct expanding (DX) refrigerant at both temperature levels (medium temperature [MT] = chilled food and low temperature [LT] = frozen food). To achieve a high energy efficiency even at
hot ambient temperatures in Amman, the system is equipped with state-of-the-art features such as:

- parallel compressors (AUX, total installed suction volume flow rate: 7.73 m$^3$/h),
- flash gas by-pass valve,
- multi-ejector,
- de-superheater downstream of the low stage compressors (LT; total installed suction volume flow rate: 16.59 m$^3$.h$^{-1}$),
- non-superheated evaporators (MT and LT). The MT compressors do have a total installed suction volume flow rate of: 25.88 m$^3$.h$^{-1}$.

Figure 3 shows a simplified system circuit.

![Figure 3: Circuit of CO$_2$ booster system operating in Amman, Jordan and picture of the applied display cabinets made by Abdin.](image)

The main components and their functions are described in the following part, starting from the lower right-hand side of Fig. 3. After heat rejection to the ambient, via the de-superheater, the discharge gas from the LT compressors merges with the vapour from the medium temperature liquid separator. When reducing the temperature of the LT refrigerant part in this way the
superheat of the merged suction gas towards the three MT compressors is within an acceptable range. Elevated superheat values could result in extreme discharge temperatures of the high pressure stage reducing the live time of the parts exposed to these temperatures at corresponding high pressure values. Heat recovery is a very attractive option for CO₂ units, therefore, the high temperature heat of the system is utilised downstream of the high pressure compressors for heating up domestic hot water. Due to heat rejection with gliding temperatures in a transcritical mode, water can be heating up to 90 °C. However, a gascooler rejects the remaining heat to the ambient air.

For transcritical CO₂ systems, it is essential to achieve a low temperature difference at the outlet of the gascooler (temperature approach), in this case after the heat rejection towards the ambient air. The energy efficiency and performance of the CO₂ system highly depends on the control of the pressure level on the high side and the temperature approach. Stene (2005) and Kauf (1999) visualized the importance of an optimum high pressure, since the coefficient of performance (COP) is directly influenced by the high pressure. A further reduction of the CO₂ temperature upstream the expansion device is achieved by an internal heat exchanger, transferring heat from the high side pressure part towards the suction flow of the parallel compressors, thus securing the required super heat.

After the heat rejection, the multi-ejectors throttle the gas into the separator at intermediate pressure level, while the traditional high pressure control valve is in stand-by mode for redundancy reasons. The multi-ejectors recover parts of the expansion work, by pumping refrigerant from the MT liquid separator to the intermediate pressure separator. Thereby, the high pressure refrigerant flow gets accelerated in a motive nozzle, thus the static pressure at its outlet drops below the medium pressure level and the refrigerant from the liquid separator is entrained and merged into the flow towards the separator, as described by Elbel and Hrnjak (2008). This means that the MT compressors are partly unloaded, i.e. load is moved from MT to the parallel compressors. The two-phase refrigerant separates after throttling in the separator. Only the liquid refrigerant is further subcooled utilizing the temperature difference between the liquid line and the exit of the LT evaporators. The subcooled liquid is supplied directly towards all MT and LT evaporators.

The higher the ambient temperature the higher the amount of flash gas increases which occurs in the separator. The parallel compressor suction group controls the pressure level in the separator. As long as there is enough vapour, as it is the case at high ambient temperatures and
when the ejectors are actively unload the MT compressors, the parallel compressors are in operation. At lower ambient temperatures, the flash gas bypass valves controls the pressure level by flashing the vapour towards the suction group of the MT compressors. The advantages of directly compressing the flash gas is on one hand avoiding throttling losses and “re- compression” with the MT compressors on the other hand the direct compression is more energy efficient, since the pressure ratio of the parallel compressors is lower compared the ratio of the MT-compressors. The largest share of the energy efficiency improvement relates to the non-superheated operation of the evaporators.

The separators downstream of the evaporators protects the compressors from liquid slugs. If liquid passes through the evaporators, either it is returned by the ejector in case of the MT part or it is utilised to sub-cool the liquid towards the evaporators. The refrigerant feeding of the evaporators is not a function of the superheat rather a function of the air temperature inside the cabinets. This enables to utilise the entire surfaces of the evaporators for cooling the air rather than to provide superheat. This results in saturation temperatures of -2 °C (MT) and -25 °C (LT) in the presented CO₂ unit in Amman, compared to temperature levels of -10 °C and -35 °C in traditional units.

The refrigerated food is displayed in refrigeration cabinets of the type Shobak, designed and manufactured by Abdin in two different versions, each optimized for their use to guarantee optimum performance and high energy savings. Equipped with double glass doors (MT version) and triple glass doors (LT version) with self-closing mechanism and the effective LED light. This kind of display cabinets, as shown on the left hand side in Fig. 1 provide a high product visibility and simultaneously reduce energy costs. Shobak is a full glass door refrigerated display cabinet for fresh pre-packed and frozen food as well as suitable for ice. The internal base is made of one PVC skin platted galvanized steel piece to prevent dirt tapping and is also inclined for easier cleaning and water disposing. PVC transparent ticket holder allow fully adjusting the PVC coated shelves.

CFC free polyurethane foam insulates the body with of a thickness of 60 mm and a density of 38-42 kg/m³. The EC fan assisted cooling system, with electronic temperature & defrost control, and electronic expansion valves (AKV) secures the even distribution of the temperature within the cabinet. The cabinets can be multiplexed and are suitable for working temperatures of 2-4 °C (MT) and -18 to -20 °C (LT).
Figure 4: Picture of the main CO$_2$ booster system installed on the backside of the supermarket building in Amman, Jordan.
Figure 5: Picture of the main CO$_2$ compressors of the booster system of the Al-Salam supermarket in Amman, Jordan.
Figure 6: Side view of the main CO₂ unit including the gascooler at Al-Salam supermarket in Amman, Jordan.
**Technical Results**

Figure 7: Monthly energy savings of the Al-Salam supermarket compared to a similar supermarket in Amman, Jordan for the period March 2018 to September 2018.

Figure 8: Monthly energy demand for the year prior the CO\textsubscript{2} unit was installed until September 2019 for the Al-Salam supermarket in Amman, Jordan.
Energy saving in the period from March 2018 to end of October 2018 was 35.729 kWh due to the implementation of the CO₂ refrigeration unit.

On an annual base approximal 40.000 kWh can be saved by the Al Salam Supermarket.

**Key Environmental Impact Numbers**

*(GHG emissions avoided (direct and indirect), Energy efficiency results)*

There are two major environmental impacts to be quantified due to the leapfrog of the refrigeration system at the Al-Salam Supermarket from HCFC-22 to CO₂ (R744), namely:

- The *indirect emission* due to energy efficiency improvements
- The *reduction of direct emissions* due to application of a natural working fluid, not affecting the Global Warming Potential

**Reduction of indirect CO₂ equivalent emissions**

The Energy mix in Jordan¹, i.e. the avoided CO₂ emissions can be estimated based on national statistical figures. However, to find an emission value for electricity in Jordan, i.e. ratio of kg₇CO₂ / kWh₇el, is currently a difficult task, due to the challenge with the previous grid / link to Egypt and Syria.

Based on various sources in the open literature, it can be assumed that approximately 90% of the electrical power in Jordan is produce with fossil fuels.

The emission values for these kind of power plants are²:

<table>
<thead>
<tr>
<th>Fuel</th>
<th>kg₇CO₂ / kWh₇el</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>1,0</td>
</tr>
<tr>
<td>Oil</td>
<td>0,76</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>0,5</td>
</tr>
</tbody>
</table>

Therefore, the following emission / power factor is applied: 0,8 kg₇CO₂ / kWh₇el

**Result:**

---

² https://www.eia.gov/electricity/annual/html/epa_a_03.html
The 40,000 kWh saved contribute to an indirect emission reduction of **annually 32 metric tons of CO$_2$.**

Reduction of direct CO$_2$ equivalent emissions

60 kg of HCFC was the original charge for all the condensing units in the previous refrigeration system at the Al-Salam Supermarket. The annual leakage rate was approximately 30%. The Global Warming Potential of HCFC22 is 1760 kg CO$_2$ / kg R22

$$20 \text{ kg} \times 1760 = 35,200 \text{ kg CO}_2 \text{ equ}$$

**Result:**

The 20 kg refrigerant leakage which now can be avoided contributes to an direct emission reduction of **annually 35.2 metric tons** of CO$_2$.

In total more than **77.2 metric tons of CO$_2$ are avoided due to the conversion of the Al-Salam Supermarket refrigeration system from HCFC-22 to CO$_2$ (R744).**

**Beneficiary and Supplier Feedback**

The beneficiary is very positive to the results they can see during the daily operation. The main feedback:

- Until October 2019, nearly two years of operation without extraordinary maintenance visits, i.e. no failure in the system nor the cabinets
- Zero food wastage due to stable temperature levels in the display cabinets
- Reduction of energy demand related to the refrigeration unit (approximately 40,000 kWh/a)
- Significant reduction in service and maintenance costs: approx. 20,000 $ / a
Challenges, Lessons learned & Recommendations

The main challenge was to find a suitable supermarket for the demonstration of the R744 technology. Several potential sites have been evaluated and different supermarket chains showed their willingness to provide a demo site. Al-Salam was chosen because of the location and accessibility to the refrigeration unit during and after the refurbishment. However, another important aspect was the real potential to include even the entire AC production (currently also a HCFC22 unit) into the R744 / CO$_2$ refrigeration unit. However, due to limited internal resources, the beneficiary couldn’t come up with the additional budget, which was required to increase the entire cooling capacity to cover also the AC part of the building.

The engagement of a local supplier and contractor was a success. The knowledge transfer from the foreign supplier of the refrigeration unit and the operation of the unit (nearly two years without any issue since the start) helped to give confidence. Now the local vendor promotes this new technology also for other projects.

The involvement of local companies, showing a real interest to further improve the know-how of the employees and demonstrating the willingness to learn is a key success factor for these kind of demonstration projects.

Training and knowledge transfer is the key for a successful and fast phase in of natural working fluid and energy-efficient refrigeration technology.

The project showed similar to other installations of this kind around the world, that first costs (CAPEX) is higher, but operational cost significantly (OPEX) lower. It is therefore very beneficial if multilateral funds, donors, initiatives are able to establish programs covering additional first costs with subsidies or affordable loans (no interest rate), so that the end-users can pay back the loan during the operational phase.
Stakeholder Quotes

“We welcome this great opportunity for Jordan to showcase our pioneering spirit and deep commitment to advance environmentally friendly solutions in all areas. We are impressed by the high technical know-how of UNIDO that was demonstrated by the implementation of the project and we are very proud of the results.” (H.E. the Minister of Environment, Mr. Ibrahim Shahahdeh)

“We are proud to confirm that Jordan is a global pioneer in the refrigeration technologies and we commend the efforts from the local companies in moving ahead towards more efficient refrigeration technologies.” (Dina Kisbi, (Former) Director of Climate Change Directorate, Ministry of Environment Jordan)

“The state-of-the-art technology has proved to be not only environmentally friendly but also energy efficient and economically superior for the retail sector.” (Firas Abdin, Business Development Manager, Abdin Industrial)

“We are happy and proud to have the trust and support from the Government in Jordan and CCAC to realize together such an innovative technology demonstration project that is expected to set a good-practice example for the entire region.” (Stephan Sicars, Director, Department of Environment, UNIDO).

“Congratulations to CCAC, the team from UNIDO and Abdin Industrial in Jordan for a successful implementation and commissioning of the first transcritical ejector supported CO₂ parallel compression system in the Middle East. The fruitful cooperation of Abdin and Enex shows that local manufacturers and suppliers of commercial refrigeration equipment are able to leapfrog towards the latest CO₂ refrigeration technology. The new refrigeration system in the supermarket in Amman, Jordan, is able to maintain chilled food at the set-point temperatures with an evaporation temperature of -2°C, while the frozen foodstuff is cooled by evaporating carbon dioxide at -25°C.” (Dr Armin Hafner, International Technical Project Advisor)