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AIR CONDITIONING AND REFRIGERATION JOURNAL

The magazine of the Indian Society of Heating, Refrigerating and Air Conditioning Engineers

COLD CHAIN

Volume 9 Number 1

Supplement to Air Conditioning and Refrigeration Journal

Single Stage, Compound, Cascade and Booster Systems and Inter-stage Cooling Methods

PLUS:

- Powering a Refrigerated Warehouse with Renewable Energy
- India Cold Chain Performance Issues
- Control Strategies for Off-Design Operation of a Transcritical CO_2 Two-Phase Ejector Refrigeration System

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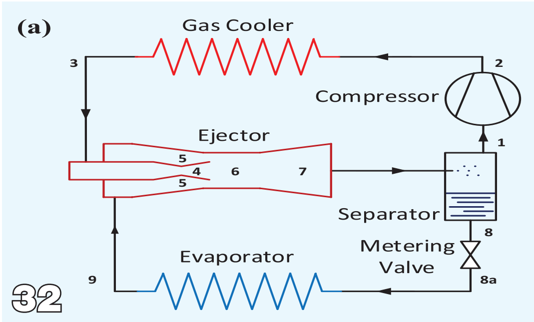

Schematic diagram of standard two-phase ejector cycle for transcritical operation

Cover design by Fezisons.

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ISHRAE
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The cold chain industry in India seems to be finally finding its rightful place in the sun. It is growing at a fast clip – about 19% CAGR – and is expected to maintain this scorching pace in the next few years. The government is supportive, having come to the conclusion that the need for food safety is served more cost-effectively by avoiding food wastage than trying to grow more food. Hence the focus on food processing and building an integrated cold chain.

The Union Budget for 2018-19 doubles the allocation for the food processing sector to Rs. 1,500 crore. There is a provision for 42 new food parks to give a boost to agri-product exports. Add to this the infrastructure status conferred on the logistics sector a few months back, and there is enough reason to believe India can emerge as a global food hub, given its large production of fruits and vegetables, milk and milk products, meat and fish and other produce.

This focus on food processing and preservation is complemented by several initiatives to double the farmers' incomes by 2020. Revamping the Agricultural Produce Marketing Committee (APMC) regime is mission-critical for achieving this objective. The Union Budget has created a Rs. 2,000 crore market fund to revamp the agricultural markets. Given the fact that the APMC regime is deeply entrenched and vested interests will fight any change tooth and nail, it will take strong political will to dismantle it – in addition to the money that has been allocated.

One area that has escaped the attention of policy-makers as well as the private sector all these years is rationalisation of the country's ancient irrigation system, which is too wastefully water-intensive for today's aqua-starved world. Drip irrigation technology has been known in India for more than half a century. And it is no rocket science. A handful of companies in the private sector have been working on this with good results, but the scale of these efforts has been pathetic. It is time to scale up drip irrigation into a national mission. This could be one of the most significant initiatives towards meeting the objective of doubling farmers' incomes. Needless to add, this will give another shot in the arm to the cold chain and food processing sectors.

ISHRAE has announced the launch of another annual exhibition-event in addition to ACREX. The first edition of RefCold will be held at Ahmedabad on November 22-24, 2018. This symbolises the emergence of the refrigeration and cold chain industry from the shadows of HVAC into its own. It mirrors the market reality, and will be welcomed by all stakeholders.

***Rakesh Kumar**, Managing Editor*

What's in Store for Refrigeration and Cold Chain Industry?

By Harshal Surange and Arvind Surange

Well, what's in store for the refrigeration and cold chain industry? ISHRAE being such a large player in the HVAC&R field, it was only a matter of time before it happened. This is the first time ISHRAE is venturing into an exclusive mega-show for the industrial refrigeration and cold chain industry, christened RefCold. The exhibition, along with the allied events being organized and created by ISHRAE and co-organised by NürnbergMesse, is being spearheaded by the dynamic and enthusiastic past president of ISHRAE, Pankaj Dharkar, who is the Chairman of RefCold. With the city of Ahmedabad being the host and Gujarat being the home state of our Prime Minister, the show is bound to be one that the entire industry will stand up and notice.

RefCold will be held at Mahatma Mandir Convention cum Exhibition Centre, Gandhinagar, Gujarat from November 22 to 24, 2018. The timing would be apt for such a show, as most cold storage owners and operators have a lull period during this time and would be free to attend it. There are a significant number of International organisations and countries that have tied up with RefCold, and hence it promises to be a truly international event.

With ISHRAE having a member strength exceeding 12000 and a student member strength of over 9000, there is a significant backup from ISHRAE for the event, which will help in creating a long-lasting brand.

ACREX 2018 had a refrigeration and cold chain pavilion, as in the last three years. However, now a decision has been made to discontinue this pavilion and organise a full-fledged RefCold instead. So this year's refrigeration and cold chain pavilion in ACREX was the last. Henceforth, ACREX will be an exclusive HVAC show along with other events under the BFA umbrella, with the 'R' in ACREX becoming the preserve of RefCold.

ACREX 2018 had a seminar and two workshops dedicated to refrigeration and cold chain, which were held concurrently with the exhibition. The seminar was held on the day before ACREX actually began, and the half-day workshops were organised on the first and second day of ACREX. All the events were well attended.

A seminar on *CO_2 Refrigeration for Supermarkets* was arranged at IIT Madras and supported by ISHRAE Chennai.

For the first time in the history of ISHRAE, four RefCon events were held in one month during January 2018, beginning with Indore on January 6, then on January 10 at Vizag, January 16 at Kolhapur and January 20 at Thane. All the events were well attended in line with ISHRAE's intent that the refrigeration and cold chain space must be well represented.

Another aspect of what's in store for the refrigeration and cold chain industry would be to look at the highlights of the recent Union Budget and its key takeaways. These are explained in the paras that follow. Many of the points are picked up from Pawanexh Kohli's article on the subject, and we thank him for the same.

Continuing the efforts towards the goal of doubling farmers' income by 2022, the Union Budget 2018 has a huge focus on agriculture and the related agri-tech sector. Various schemes and measures announced in the budget are aimed towards increasing the market reach and sale realisations for the farmers as well as facilitating higher production.

Some key highlights of the budget related to the agri sector are:

- Develop and upgrade 22,000 Grameen Agriculture Markets (GrAMs) in rural areas to serve as direct markets as well as aggregation and dispatch hubs to collect, package and transport produce to bigger markets at the individual or collective level.
- Expand eNAM coverage for farmer welfare by connecting 585 APMCs to eNAM and enable online sale of produce from farmers directly to consumers and bulk purchasers. This objective complements the Digital India initiative wherein the government proposes to set up 5 lakh wifi hotspots in rural India. This move has the potential to bring a change in the way farmers operate and sell produce.
- Ensure Minimum Support Price (MSP) for farmers growing *Kharif* crops at 1.5 times the cost of production. This will in turn ensure liquid cash with farmers that will increase their investment in agri tools.
- 'Operation Green' will be launched by the government for development of the entire chain from the farm to the consumer for potatoes, onions and tomatoes.
- Kisan Credit Card benefits have been extended to animal husbandry, fisheries and aquaculture sectors.
- The budget allocation for food processing has been doubled, thus continuing the efforts towards reducing food waste, setting up food parks and improving food quality. This should prove beneficial for exports as well as attracting investments from international chains.
- Other financial benefits like income tax exemption for the next five years for FPOs with turnover under Rs. 100 crores, raising institutional credit for agriculture, and allocation for irrigation development to focus on 96 districts where less than 30 per cent of the land holding receives assured irrigation.

Overall, the budget looks positive towards providing various measures to increase farmers' incomes and boost the domestic and export food market for India. The focused effort on increasing food production, facilitating direct, aggregated as well as online sale, investment in food processing sector along with liberalisation of agri-commodities exports, look promising for our agri-based economy. And this should create a lot of opportunities for cold storage, supply chains, logistics, packaging and related industries. Incentives like tax exemption on some of the cold chain components, subsidies for setting up new cold chain facilities, etc. will continue to provide the required boost to the cold chain industry.

Operation Green would be the next big thing and we should see a lot of work happening around the three products that the scheme focuses on.

About the Authors

Harshal Surange is a consultant and handles Cold Chain and HVAC projects. He is a past president of ISHRAE Pune chapter and founder president of IIAR Western India Chapter. He was the winner of Bry-Air Award in 'Excellence in System Design' category in 2009. He was a part of the 15-member Indian delegation for the US Cold Chain Study Tour sponsored by USTDA, and can be contacted at *acr.consultants@gmail.com*

Arvind Surange is a consultant in Cold Chain and HVAC projects for over 40 years. He is a Fellow, ASHRAE and is past president of ISHRAE HQ and ASHRAE WIC. He is the author of '*Cold Storage Basics*' published by ISHRAE, and is a member of the technical committee of NHB. He was conferred Lifetime Service Award by ISHRAE.

RefCold India

to Make its Debut in November 2018

REFCOLD INDIA
22 - 24 NOVEMBER, 2018
Mahatma Mandir Convention Cum Exhibition Centre, Gandhinagar, Gujarat
www.refcoldindia.com

Come November 2018, the Refrigeration and Cold Chain industry in India would witness the coming together of the best of technology and business at a grand scale.

The Indian Society of Heating, Refrigerating and Air Conditioning Engineers (ISHRAE) and NürnbergMesse India have launched a brand new exhibition for the Refrigeration and Cold Chain industry, and it is called RefCold India.

RefCold India will be a one-of-its-kind exhibition whose sole objective would be to ensure a well-rounded growth of the Refrigeration and Cold Chain industry in India. It would lead to augmentation in business, innovation, technology and sustainability.

The event, in effect, would be an endeavor to cover all the varied sections of the refrigeration and cold chain industry and bring together the vast base of business prospects under one roof. It will also be the arena for the global investment community to connect with stakeholders in the Refrigeration and Cold Chain industry in India.

RefCold India would mark its debut on November 22, 2018. It would be a three-day event that will close on November 24, 2018. The venue, Mahatma Mandir Convention Cum Exhibition Centre in Gandhinagar, Gujarat is aptly chosen for its size, grandeur, technological preparedness and the distinct character reflecting the prosperity of Gujarat. All details with regards to the event can be looked up on the live website: *www.refcoldindia.com*

A hugely successful launch indicates an equally positive debut

RefCold India got launched on January 10 at The Hyatt Regency in Ahmedabad and got an impressive turnout of over 300 professionals and veterans from the industry. The launch show generated a very encouraging response, with industry leaders confirming their partnership.

Confirming the above associations, Pankaj Dharkar, Chairman of RefCold mentioned, "We are thrilled to have finally launched RefCold India. The Refrigeration and Cold Chain Industry in India needed a symposium where the focus would be solely on this sector. From its debut year itself, RefCold India would cover all aspects of the industry, which mainly are – the resources (cold chain services), the process (cold transportation and equipment) and the products (cold storage and equipment). I welcome all associates, partners, visitors and media to this promising platform and am confident that it would help us take the industry to the next level of knowledge and business exchange".

In global terms also, the Cold Chain Industry in India is developing at a much faster pace, owing to the general change in the business outlook. While earlier, the focus at all times would be on increasing the production level, the market now is concerned with optimizations in terms of better storage and transportation facilities for their respective commodities. Hence, Cold Chain management has now become an integral part of the supply chain industry comprising of refrigerated storage and refrigerated transportation. This makes it essential for all businesses to invest in infrastructure that should help reduce wastage. With this promise and prospect, the cold chain industry in India is forecasted to grow at a CAGR of 19% during the period of 2017-2022.

"As a country, India is much ready for a consortium of this level, which shall be the launch-pad for potential business-enabling collaborations, as well as the live resource pool and aggregation of Cold Chain products, services and solutions", Vishal Kapur, the President of ISHRAE, expressed his enthusiasm with this event. "I am absolutely convinced that RefCold India in November 2018 will be a greatly successful show that would leave a mark on the Refrigeration and Cold Chain market in India", said Kapur.

The Indian Edge – Some Facts

- Second largest arable land in the world
- Largest producer of milk and second largest producer of fruits and vegetables
- Largest livestock population
- Rising consumption expenditure
- Strategic geographic location in terms of exporting processed foods
- Favourable government policies to boost the cold chain industry
- The state's focus to increase export produce and reduce wastage

Also present at the event, Sonia Prashar, Chairperson of the Board and Managing Director of NürnbergMesse India Pvt. Ltd. mentioned, "There would be representation and participation from all possible arteries of the industry. We are anticipating a great response across the food industry, trading and distribution sectors, transportation lines, storage companies, shipping and ports, pharamaceuticals, hospitality, horticulture departments and the whole range of researchers and innovators. We strive to achieve this and mark a successful debut as we collaborate efforts with regards to planning, implementation, marketing and value creation for our exhibitors and visitors alike. I urge everyone to follow this event and participate with full force."

Websites: *www.ishrae.in, www.nuernbergmesse.de, www.nm-india.com*

Update on the Activities of
CII National Cold Chain Task Force

By Purushothaman Ravichandran
President, Danfoss India and
Chairman, CII National Task Force on Cold Chain Development

Activities Planned in 2018

Given the Government's priority for doubling farmers' incomes, India needs to bring about a supply chain revolution for creating capacities and efficiencies in the supply chain network from the farm to the fork. With this agenda, the CII National Task Force on Cold Chain Development plans to undertake the following activities during this year to develop a holistic cold supply chain network in the country.

Impact Analysis of Existing Cold Chain Infrastructure

The project aims to carry out an impact analysis of the integrated distribution and logistical system that was built in Pune. The impact analysis will be done in terms of value created for farmers and consumers based on better returns to the farmers and availability of quality and fresh produce to the consumers compared to what they get in a conventional supply chain.

Ease of Doing Business

The study aims to provide recommendations on the framework for fast-track procedure or single window clearance to ease the setting up of cold chain infrastructure and the ways to tackle the operational challenges faced by cold store owners. It will also enable easy adoption of new technologies. The study is being conducted in nine states, namely Himachal Pradesh, Punjab, Haryana, Telangana, Andhra Pradesh, Odisha, West Bengal, Gujarat, and Maharashtra.

Revival of Existing Cold Chain Infrastructure in West Bengal

The project aims to assess the current condition of the existing infrastructure at 36 pre-identified sites and provide recommendations related to technology upgradation, creating a sustainable agri supply chain model and draw up a detailed map of market linkages in the state. This will help the industry and business to expand their market and provide the right value to both farmers and consumers

Southern Grid as Distribution Hub for Agri Commodities

The project looks forward to connecting all the major consumption centers of Southern India through an integrated supply chain network via road and rail. The distribution centers will connect the southern produce and provide the required volume to scale up the operations of moving it to the northern region by overcoming challenges pertaining to marketing infrastructure, facilities for packaging, proper loading and unloading, etc. to ensure timely delivery of fresh perishable products.

Pilot Study in Andhra Pradesh for Inland and Marine Fisheries

The study is proposed to be conducted with the objective of viability assessment for marketing of marine and inland fisheries in the state of Andhra Pradesh. There is a strong need for the cold chain industry to come up with innovative and cost effective logistics solutions to ensure supply of safe, hygienic and nutritious fish to the consumer at a reasonable price. The project seeks to present a supply chain model for the marketing of fisheries and marine products in the country in an organized manner.

Training and Capacity Building

Looking at the entire agri value chain and need of the cold chain Industry, training programs are planned to be conducted on best practices in cold chain and handling operations to professionals of the cold chain industry.

Research and Studies

To explore the potential of the sector, need based market research and studies are being conducted to identify the gaps, undertake crop and state specific feasibility reports and value chain assessment of various agri commodities.

Cold Chain Awards

The third edition of CII Cold Chain Awards Program, supported by NCCD, has been launched with the intent of promoting standards for excellence across business operators in India. This year, applications are invited in the following categories: Innovation in Cold Chain Technology or Business Model; Best Practices in Reefer Transport; Packhouse; Ripening Chamber; Best Integrated Supply Chain Solutions; and Best Practices in Cold Storage. For more details and for downloading the application form, please visit *http://face-cii.in/sites/default/files/2018/3rd-cii-cold-chain-award/LOI%20CCA%20.pdf*

The last date for submitting the duly filled applications is May 31.

About the Author

Ravichandran Purushothaman is the President of Danfoss India. He has been with Danfoss since 2002. With over 25 years of experience, Ravichandran has held roles spanning across sales and distribution, business development, project management, change management and general management functions in India and Asia Pacific regions. He is an electronics and communication engineer who completed his management education program from IIM Ahmedabad.

New Products from Elanpro

Flexi Drawer

It is a fridge and freezer model that fits underneath the countertop in place of a cabinet. The product comes with variable temperature options to ensure that food is maintained at the right condition. It is energy efficient, convenient, safe and reliable for optimal storage for a wide range of products.

Garbage Cooler

Elanpro ECC-120 garbage cooler

It is natural for garbage in the trash bin to decompose and emit an unappetizing stench. Elanpro has launched Garbage Coolers, a professional range of coolers for refrigerated storage of food waste that refrigerates the garbage to stop further decomposition until its final collection. The product is suitable for restaurants and commercial kitchens as well as shops that prepare and/or sell perishable food items.

Counter Top Chiller

It is a space saving and energy efficient solution for frozen commercial storage needs. With a small footprint and lightweight design, Elanpro Counter Top Freezer is suitable for supermarkets, restaurants, delis, bakeries and convenience stores looking to expand their offerings display, while saving valuable counter space.

Bakery Range

Elanpro Bakeshop RPC

Elanpro has introduced four new variants to its confectionary showcase range. Bakeshop DC Series boasts of high performance and aesthetics that create a reliable and technologically advanced display showcase. Bakeshop RPC enhances the shelf life of confectionery products in cold, hot and ambient temperature. Elanpro Buffet Freezer is a streamlined solution for storage and display, suitable for buffets, banquets and catering events. New variants have been added to pastry cabinets and counter top display range.

Professional Kitchen Range

Sushi Case is equipped with ventilated refrigerated preparation counters and a glass canopy. It combines robust construction and high efficiency.

For more information, visit http://*www.elanpro.net/*

MPEDA Expects Seafood Exports to Cross $6 bn in Current Fiscal

Stakeholders from across the Indian seafood industry were optimistic that marine products exports would reach Rs 50,000 crore in the next few years given the current growth curve and strides made in aquaculture production. They were talking at the 21st edition of the three-day biennial India International Seafood Show (IISS) which was held in Margao.

Goa Chief Minister Manohar Parrikar, who inaugurated the event, said that while the east coast, especially Andhra Pradesh, was surging ahead in culture fisheries, the west coast could enhance their contribution to exports in coordination with organisations like the Marine Products Export Development Authority (MPEDA). He added that the country should do more to make use of the fishing potential along the underutilized but large Andaman and Nicobar coastline.

He said that sustainable deep sea fishing should be explored and issues like sea water pollution from chemical fertilizer wash-off, over-exploitation of existing fishing zones and damage to breeding grounds should be tackled. "India has the potential to become a seafood superpower and the goal of 20 per cent growth or doubling of the export volumes will not be as difficult if we tap into this potential fully," he said. In 2016-17, India exported 11,34,948 million tonnes (MT) of seafood, principally frozen shrimp and frozen fish, worth 37,870.90 crore and provisional export figures for April-November 2017 have shown an increase of 18.72 per cent and 15.16 per cent respectively in quantity and value (in terms of US dollars) of seafood exports.

The export earnings are expected to cross a high of US$ 6 billion during the current fiscal, buoyed by aquaculture growth, enhanced processing capacity and favourable market conditions, MPEDA chairman A. Jayathilak noted. "If we are able to sustain our efforts in production, India can become the second largest exporter of seafood after China within a few years surpassing countries like Norway, Vietnam, the US or Thailand," he added.

Manohar Parrikar inaugurates India International Seafood Show

Goa's Minister for Agriculture, Vijai Sardesai, who presided over the function, pointed to over-exploitation as a major concern and called for proactive measures to avoid situations like the 'fish famine' affecting southeast Asian countries. "Goa is taking strict measures such as a ban on LED lights to curb damaging fishing practices, but bigger states also need to do their bit if we wish to have sustained exports," he said.

Vinod Palyekar, the state's Minister for Fisheries and Water Resources said they were planning to set up a Fisheries Corporation in Goa with the dual aim of increasing exports and ensuring that fish is available to domestic consumers at reasonable prices. Seafood Export Association of India president V. Padmanabham highlighted the challenges faced by seafood producers and exporters and hoped that the deliberations at IISS 2018 will help address some of these issues.

The event drew over 3000 delegates including exporters, suppliers and researchers, and 2000 visitors from India and countries like the US, the UK, Spain, Japan, Australia, China, Vietnam, South Korea, Thailand, Malaysia and those in the Middle East, organisers said.

(Source: Business Line, January 31, 2018)

Amazon is First Foreign e-Commerce Firm in a Food Retail Venture In India

Amazon has rolled out its own food retailing business in India with a pilot in Pune, becoming the first foreign e-commerce firm to stock and sell food items directly to consumers.

"Amazon is now a vendor on Amazon.in and is currently operating in Pune," said a person familiar with the development. The products are sold by Amazon Retail India Pvt. Ltd.

Another person said it will take 'at least a quarter' for the e-commerce major to roll out its food retailing business nationwide.

Amazon had last year secured the government's permission to invest $500 million in a wholly-owned venture to retail locally produced and packaged food products through offline and online channels. It is the only global entity to have applied for the food-only retailing business, an area where the government allowed 100% overseas investment in 2016 to help producers and generate employment.

"We continue to be on track to launch our food retail business in India," an Amazon India spokesperson said without giving details. The development comes at a time when Amazon's global rival Walmart is in talks to purchase a stake in India's homegrown e-commerce company Flipkart.

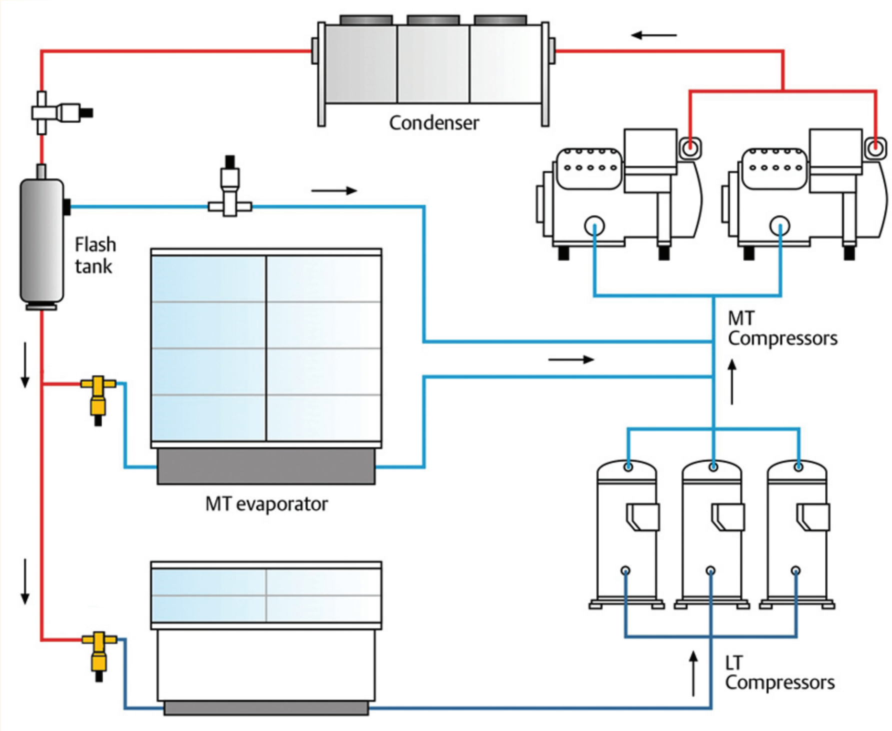
When India opened food-only retailing to foreign direct investment (FDI) in 2016, food processing industries minister Harsimrat Kaur Badal staged roadshows in London to woo retailers such as Tesco and Marks & Spencer, but the response was muted.

Global retailers including Walmart have shied away from the segment, arguing that selling only low-margin food items does not make economic sense and such ventures should be allowed to stock non-food items such as shampoos and detergent soaps.

The government, while clearing Amazon's proposal in July, asked it to maintain separate management and offices for the venture and keep them distinct from its marketplace business which is not allowed to sell products directly to consumers. Foreign-funded BigBasket, Grofers and Supr Daily have also received similar approval for food retailing.

(Source: retail.economictimes.indiatimes.com, February 19, 2018)

A simple two-stage CO_2 booster system (Courtesy: Emerson)



Single Stage, Compound, Cascade and Booster Systems and Inter-stage Cooling Methods

By Ramesh Paranjpey
Fellow ASHRAE Life Member, Pune

Introduction

This article discusses various refrigeration systems and differences between:

a. Single stage, two stage and cascade systems,
b. Single frame two stage compressor inter-stage cooling systems,
c. Various methods of inter-stage gas cooling, their advantages and drawbacks, and
d. Performance comparisons of various methods.

Compressor and Compression Ratio

First, we need to understand the function of a compressor in a closed cycle refrigeration system.

The function of a compressor in a vapour compression refrigeration system is to draw the low temperature low pressure saturated or superheated vapour from the evaporator and raise its energy level so that it is able to reject heat to the cooling medium, either initially to water and then to the atmosphere, or directly to the atmosphere in an air cooled system.

Since heat always flows from high temperature to low temperature, it is necessary to raise the energy level of the refrigerant beyond the condenser cooling water temperature in case of water cooled systems or air temperature in case of air cooled systems for rejecting heat.

The compressor performs this function of raising the energy level and is the most important part in the refrigeration system, as it is the only moving component in the system and is also the most expensive equipment. The compressor therefore needs to be protected since any fault anywhere in the system finally results in malfunction or breakdown of the compressor.

The problems that cause compressor malfunction or breakdown are generally:

1. System contamination caused by dirt, dust or other material coming from the internals of piping, e.g. welding material.
2. Liquid reaching the compressor due to faulty plant design, installation or operation.
3. High operating temperatures beyond allowable limits; these conditions could be due to high superheat of gas at compressor entry, non-condensable gases, *high discharge pressures, high compression ratio*, etc.

About the Author

Ramesh Paranjpey is a mechanical engineer with an M. Tech. in refrigeration from IIT Bombay, having over 35 years' experience. He has worked in very senior positions with Kirloskar Pneumatic in Pune, Carrier Transicold in Bangalore and Singapore and Voltas-Air International in Pune. Presently, he works for himself as a technical advisor and consultant. He is an ASHRAE Fellow, past president ASHRAE W.I. Chapter and past president ISHRAE Pune Chapter. He can be contacted at ramesh.paranjpey@gmail.com

Compression ratio is the ratio between *absolute* discharge pressure and *absolute* suction pressure.

As the evaporator temperature and pressure decrease, compression ratio increases and therefore the discharge temperature goes up.

While designing Industrial Refrigeration systems, especially for *low temperature* applications using ammonia as the refrigerant, many times we come across a system where the compression ratio exceeds 10 to 12 and it is then obvious that a two-stage system would be a better choice than a single stage system. The manufacturer's capacity charts also prohibit use of compressors beyond a certain difference between saturated condensing temperature (SCT) and saturated suction temperature (SST) and not saturated evaporating temperature (SET).

High compression ratio causes:

1. Loss of efficiency.
2. High discharge temperatures.
3. Carbonization of oil and reduced viscosity, affecting lubrication.
4. Damage due to high bearing loads.
5. Excessive wear.

Table 1 shows isentropic discharge temperatures for various refrigerants currently used in a typical low temperature application, say at -20°C evaporating and +40°C condensing temperature.

Table 1: Isentropic discharge temperatures for refrigerants used in a typical low temperature application

Refrigerant	Cp/Cv at boiling point or at atmospheric pressure	Approximate isentropic discharge temperature, °C
R22	1.236	75
R134a	1.154	55
R404A	1.166	58
R410A	1.244	70
R717 (ammonia)	1.348	145

Where,

Cp is specific heat at constant pressure,

Cv is specific heat at constant volume,

Cp/Cv is known as index of compression and generally represented as 'γ'.

As can be seen from *Table 1*, for similar operating compression ratio, ammonia compressors will have higher discharge gas temperatures compared to other refrigerants.

The maximum allowable discharge gas temperature is 130-140°C with use of mineral oils for compressor lubrication. If the isentropic temperature exceeds this limit, it is always advisable to go for multi-staging. As a thumb rule, if the allowable temperature difference between SCT and SST is more than 50°C for ammonia and 70°C for R22 and other refrigerants, it is advisable to design two-stage systems.

Many compressor manufacturers also indicate in their published ratings the allowable difference between saturated discharge and suction temperatures, thus limiting the use of single stage compressors.

Since low temperature applications require high compression ratios, they are accomplished by carrying out compression in two or more stages. The discharge from the first compression stage becomes the suction of next stage after the superheat of the gas is reduced.

Single and Two-stage Compression

The simplest way to explain the difference between a single stage compressor and dual or two-stage compressor is the number of times that the refrigerant is compressed. In a single stage system, the refrigerant is compressed once and in a two-stage system the refrigerant is compressed twice.

In a single stage reciprocating compressor the refrigerant is drawn into a cylinder and compressed in a single piston stroke, and then the refrigerant goes to the condenser as shown in *Figure 1*.

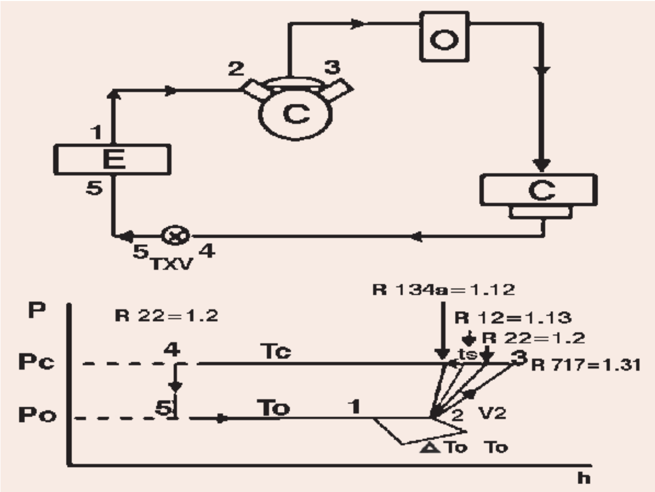


Figure 1: Single stage compression

A system with multiple compressors running in parallel without any inter-stage cooling is considered as single compression, not as a compound or two-stage system.

Compound Refrigeration System

A compound system uses two or more compressors – reciprocating, screw or centrifugal – *in series* using a single refrigerant. *The system could be two-stage, three-stage or even more, depending upon the application and low temperature required to be achieved.*

A compound system must therefore include additional components such as intercooler, economizer or sub-cooler to improve the system efficiency. A two-stage system is in fact a compound system having a combination of two single stage systems with an intermediate intercooler.

In two-stage compression, the first step is the same except that the refrigerant from the low stage is not directed to the condenser; it is sent via an intercooler. The discharge gas superheat is then reduced and the saturated or slightly superheated gas goes to second high stage suction and is compressed again before going to the condenser. The final discharge gas temperature is therefore much lower than if compression had taken place in single stage, as shown in *Figure 2*.

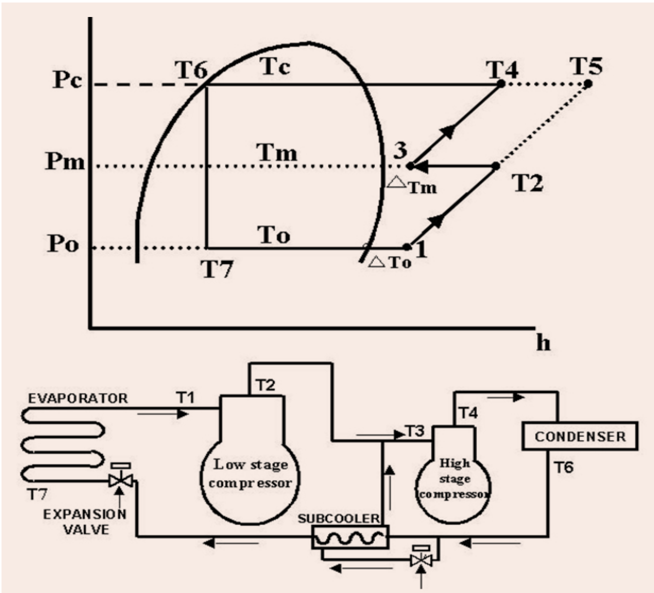


Figure 2: Two-stage compression

Two-stage Operation

If the compression ratio tends to go beyond 8 to 10, many times it is found that a two-stage system operation is much more economical, consumes lower power and leads to overall lower compressor displacement and lower discharge temperatures.

A two-stage operation uses the same refrigerant for high and low stages, and the inter-stage cooling of the low stage gas is achieved by various designs leading to its de-superheating before it goes to the high stage suction. This ensures lower intermediate and final discharge gas temperatures.

A two-stage system can be with two different compressors or with an inbuilt single frame compressor in which the cylinders are arranged in such a manner that some cylinders operate as the high stage and the remaining cylinders operate as the low stage.

Advantages of Two-stage Systems

- Increase in the refrigeration effect.
- Removal of flash gas in the inter-stage cooler.
- Reduced discharge gas temperature.
- Reduced equipment size.
- Reduced system power consumption.
- Reduced annual operation expenses.

Normally a two-stage system operates most efficiently when the pressure ratio for the low stage and the high stage is equal or, in other words, intermediate pressure is a square root of the overall compression ratio; $Pi = \sqrt{Pc \times Po}$. This is the ideal intermediate pressure and saturated temperature and is possible when the number of high stage cylinders is half the number of low stage cylinders. For example, a 6-cylinder compressor with four low stage and two high stage cylinders has higher efficiency compared to five low stage and one high stage cylinder arrangement; however, one can achieve much lower evaporating temperatures easily with the second arrangement.

If two separate compressors are used, the application engineer can select the proper intermediate pressure; however, if he is using uni-built single frame design of a compressor, the selection of intermediate pressure depends upon the cylinder ratio of high and low stages for the particular compressor model.

Inter-stage Cooling

Four inter-stage gas cooling methods are normally used for two-stage application. These are:

A. Direct injection of liquid for gas cooling in the inter-stage system.

B. Direct injection with inter-stage gas and liquid cooler system.

C. Open type flash cooler system.

D. Closed flash type inter-stage cooler system.

We shall now discuss each of these methods in greater details and their advantages as well as disadvantages.

System A: Direct Injection of Liquid for Gas Cooling in the Inter-stage

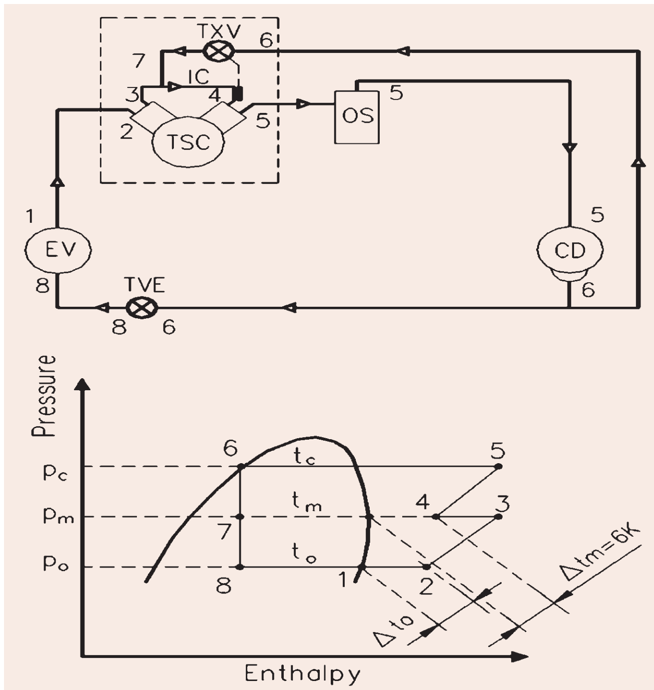


Figure 3: Direct injection of liquid for gas cooling in the inter-stage

Legend

TSC	: Two stage compressor	Qo	: Compressor capacity
IC	: Injection inter-stage cooler	Pe	: Compressor shaft power
TXV	: Thermostatic expansion valve	n	: Maximum rotational speed
OS	: Oil separator	Δtc	: Liquid sub-cooling
CD	: Condenser	Δtm	: HP suction superheat
TVE	: Throttle valve for feeding evaporator	Δto	: LP suction superheat
EV	: Evaporator	Pc	: Saturated condensing pressure
t_c	: Saturated condensing temperature	Pm	: Saturated intermediate pressure
t_m	: Saturated intermediate temperature	Po	: Saturated evaporating pressure
to	: Saturated evaporating temperature	h	: Enthalpy

System Description

The discharge from the two-stage compressor goes to the oil separator and then to the condenser. From the condenser/ receiver, two liquid outlets '6' are taken out, of which one is the main liquid outlet that goes to the evaporator through an expansion valve from '6' to '8'. The evaporated gas '1' is then sucked by the compressor low stage cylinders '2'. The discharge of low stage cylinders '3' enters the inter-stage cooler (sub-cooler), which is an integral part of the compressor in the form of pipe joining low stage discharge to high stage suction. A small amount of liquid from the receiver outlet in the second stream is brought to this intercooler pipe. There is a thermostatic expansion valve in this line, whose bulb is fitted on the suction side of HP cylinders. The expansion valve controls gas superheat before it enters the HP cylinders. The purpose is to ensure that no liquid is entering the HP cylinders. The gas is then again compressed in the HP cylinders before it enters the oil separator and then the condenser.

Many users provide a temperature sensor in the discharge gas and a combination of solenoid valve and hand expansion valve. Sensing the compressor discharge temperature, the solenoid valve opens or closes whereas the hand expansion valve expands a fixed quantity of liquid to enter HP cylinders.

This is an incorrect practice since, if the compressor is operating on partial load, the hand expansion valve would still supply the same quantity as per its setting and there are chances of extra liquid getting admitted to HP cylinders. Also, if due to certain other reasons such as valve plate leakage or gasket rupture the discharge gas temperature is high, the solenoid valve would open and hand expansion valve would still continue to feed liquid-vapour mixture to HP cylinders when it is not needed.

The crux is we need to control superheat at the entry to HP cylinders and not the discharge gas temperature at the outlet of HP cylinders.

We shall now discuss some advantages and disadvantages of this system.

Advantages

1. Inter-stage cooling section is very simple and inexpensive; no need for additional isolation shut off valves, oil separator in the LP discharge line or suction strainer in the HP suction line.
2. The complete system can be built on to an integral two-stage compressor, thus saving floor space in the machine room.
3. The system is easy to install and control.
4. This system is suitable for all refrigerants.

Drawbacks

1. Since liquid expansion is only in one step from condensing pressure to evaporating pressure, there is no increase in evaporator capacity (enthalpy). Hence the system has a lower refrigeration capacity compared to other systems.
2. This results in relatively high specific power consumption (kW/ TR).
3. Hunting of expansion valve may happen, especially at reduced loads.
4. Under certain conditions and required capacity, you may need higher size or the next higher compressor model compared to other systems, or for the same requirement you may have to run the compressor at a higher speed compared to other systems.

System B: Direct Injection with Inter-stage Gas and Liquid Cooling

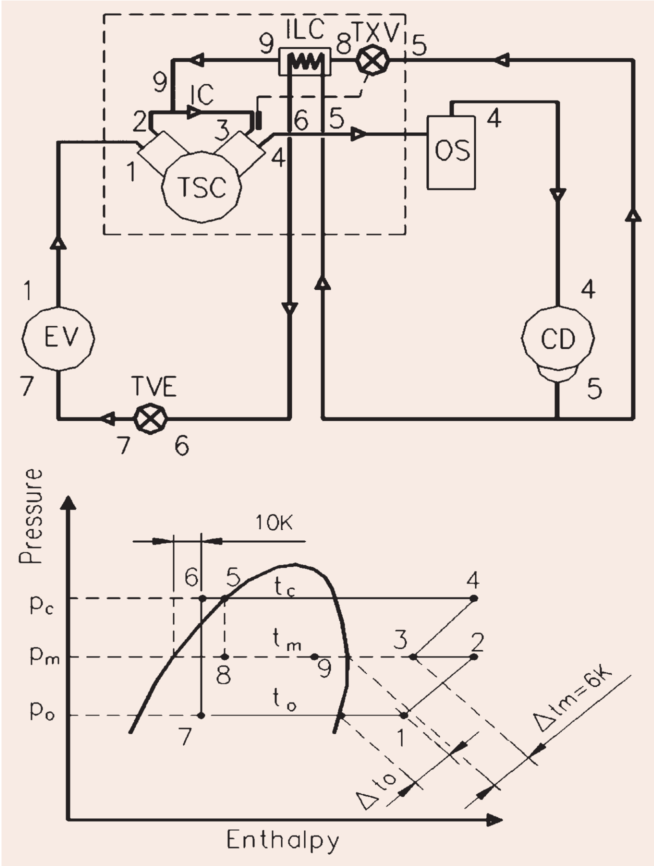


Figure 4: Direct injection with inter-stage gas and liquid cooler

Legend

A = TSC	: Two stage compressor	Qo	: Compressor capacity
B = IC	: Injection inter-stage cooler	Pe	: Compressor shaft power
C = TXV	: Thermostatic expansion valve	n	: Maximum rotational speed
D = OS	: Oil separator	Δtc	: Liquid sub-cooling
e = CD	: Condenser	Δtm	: HP suction superheat
f = TVE	: Throttle valve for feeding evaporator	Δto:	LP suction superheat
g = EV	: Evaporator	Pc	: Saturated condensing pressure
t_c	: Saturated condensing temperature	Pm	: Saturated intermediate pressure
t_m	: Saturated intermediate temperature	Po	: Saturated evaporating pressure
t_o	: Saturated evaporating temperature	h	: Enthalpy

System Description

This is an extension of system A, where condenser liquid is not injected directly in to the inter-stage gas cooler but circulated through a *dry expansion chiller* in which the full high-pressure refrigerant liquid flow is sub-cooled down to a certain temperature difference above the saturation intermediate temperature, say about 10K.

Advantages

1. Thermodynamically identical alternative as for system D.
2. It has the same favorable refrigeration capacity and power consumption, but much smaller liquid content of inter-stage cooler and trouble free oil return to HP cylinders.
3. Inter-stage cooling section is smaller, simpler, less expensive and more convenient than system D.
4. It can be built on the compressor like system A, resulting in saving of space.
5. As with system A, no LP oil separator, HP suction strainer or isolation valves between stages are required.

Drawbacks

1. Hunting of expansion valve may happen at reduced loads.
2. This system is more suitable for R22 and R404A applications and is seldom used in ammonia applications.

System C: Open Flash Inter-stage Cooling

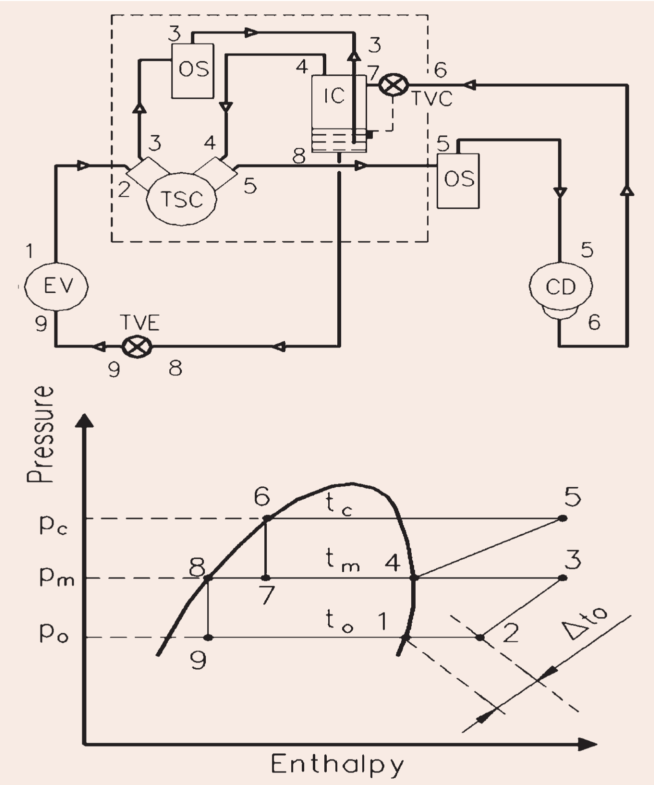


Figure 5: Open type flash cooler system

Legend

A = TSC	: Two stage compressor	Qo	: Compressor capacity
B = IC	: Injection inter-stage cooler	Pe	: Compressor shaft power
C = TXV	: Thermostatic expansion valve	n	: Maximum rotational speed
D = OS	: Oil separator	Δtc	: Liquid sub-cooling
e = CD	: Condenser	Δtm	: HP suction superheat
f = TVE	: Throttle valve for feeding evaporator	Δto	: LP suction superheat
g = EV	: Evaporator	Pc	: Saturated condensing pressure
t_c	: Saturated condensing temperature	Pm	: Saturated intermediate pressure
t_m	: Saturated intermediate temperature	Po	: Saturated evaporating pressure
t_o	: Saturated evaporating temperature	h	: Enthalpy

System Description

Inter-stage cooling takes place by passing the full hot discharge gas from LP cylinders through a liquid ammonia refrigerant inside the vessel, called open flash cooler. The gas gets condensed and reaches intermediate pressure. This is achieved by passing full liquid refrigerant flow from the high-pressure condenser and expanding it through a throttle valve to intermediate pressure. Both the gas from low stage and the expanded liquid/flash gas from high stage mix and the mixture reaches equilibrium at intermediate pressure.

The saturated liquid from this intermediate vessel is then further expanded through a throttle valve to the required temperature and pressure and fed to the evaporator either directly or through LP vessel if it is a force-feed ammonia pump circulation system.

An important point to be kept in mind while using open flash cooler is that the mass flow rates in lower stage and higher stage are different. The high stage will have more refrigerant mass flow rate since it has to absorb heat equal to refrigeration load plus heat of compression of low stage. This does not mean that more swept volume is required in high stage. In fact, much lower swept volume is required since the density of gas is higher at intermediate pressure and temperature compared to low stage suction conditions.

Advantages

1. The refrigeration effect is higher compared to all other systems for the given operating conditions. (The enthalpy difference is the maximum.)
2. This results in minimum power consumption for the required refrigeration effect.
3. C.O.P is the highest or kW/TR is the lowest.
4. This results in minimum operating cost, especially where the running time per year is very high.
5. This results in less refrigerant mass flow and thus needs a smaller compressor or the same compressor at lower RPM.

Drawbacks

1. Inter-stage cooling section is complicated and expensive due to the necessity of shut off valve, additional oil separator in the LP discharge line and a suction strainer in HP suction line.
2. It requires automatic capacity control to load and unload cylinders as per variation in load and suction pressure.
3. An expensive set of level controls are required for intermediate pressure vessels and extra safety valve, drain valve and purge valve are needed.
4. It requires extra floor space in the machine room to accommodate inter-stage cooler and its controls.
5. Installation is less convenient since the intermediate vessel is required to be located above LP vessel in case of ammonia pump circulation systems as the pressure difference across the throttle control valve is low and many times liquid feeding in evaporators/LP vessels becomes a problem if sufficient care is not taken to ensure minimum

pressure drop in the liquid line from intermediate vessel to evaporators/LP vessel.

6. There is a risk of flash gas formation in liquid line from inter-stage cooler to evaporators.
7. Inter-stage cooler contains a considerable volume of liquid refrigerant and traps oil coming from LP stage, therefore it is less suitable for HFC/HCFC refrigerants.
8. It requires a skilled operator to operate the system.

System D: Closed Flash Inter-stage Cooler

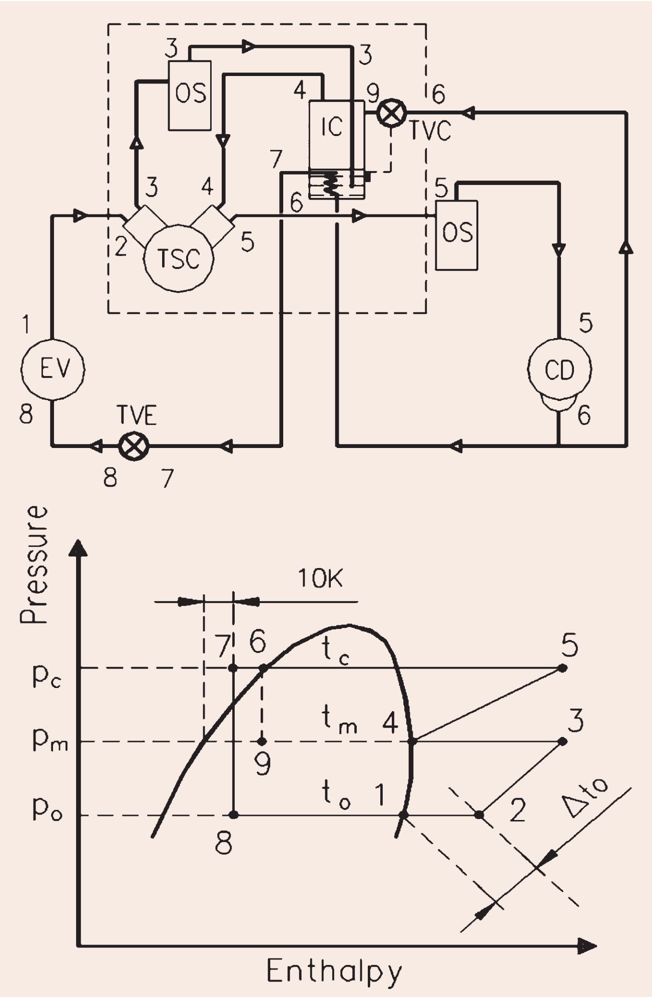


Figure 6: Closed flash type inter-stage cooler

Legend

A=TSC	: Two stage compressor	Qo	: Compressor capacity
B=IC	: Injection inter-stage cooler	Pe	: Compressor shaft power
C=TXV	: Thermostatic expansion valve	n	: Maximum rotational speed
D=OS	: Oil separator	Δtc	: Liquid subcooling
e=CD	: Condenser	Δtm	: HP suction superheat
f=TVE	: Throttle valve for feeding evaporator	Δto	: LP suction superheat
g=EV	: Evaporator	Pc	: Saturated condensing pressure
t_c	: Saturated condensing temperature	Pm	: Saturated intermediate pressure
t_m	: Saturated intermediate temperature	Po	: Saturated evaporating pressure
t_o	: Saturated evaporating temperature	h	: Enthalpy

System Description

This is a variant of system C, where inter-stage gas cooling takes place in a similar manner, but the liquid refrigerant flows under condensing pressure in a closed cooling coil in the interstage vessel and then goes to the throttle valve and the evaporator/LP vessel. A small part of the liquid from receiver is throttled and injected just in enough quantity required for interstage gas cooling. In the coil, which is maintained at condensing pressure, it is subcooled down to a certain temperature difference (10K) above the intermediate saturation temperature.

Advantages

1. It is an alternative to system C without its disadvantages.
2. Full pressure difference between condenser and evaporator is available to properly operate throttle valve for evaporator.
3. The liquid is subcooled and there is therefore hardly any risk of flash gas bubbles in the liquid line from interstage to evaporator.
4. The interstage vessel can be conveniently installed in the machine room and is not required to be elevated, unlike in system C.
5. Operation is simpler than system C and does not require a very highly skilled operator.

Drawbacks

1. The refrigeration capacity at the given conditions is somewhat lower than system C, approximately 3 to 5%, due to higher enthalpy of liquid-vapour mixture at evaporator inlet.
2. It requires automatic capacity control to load and unload cylinders as per variation in load and suction pressure.
3. Specific power consumption is therefore somewhat higher than system C.
4. Interstage cooler is more expensive due to closed cooling coil inside the cooler.

Thermodynamic Comparison of Inter-stage Cooling Systems

Example: Model with 7 low stage and two high stage cylinders; SCT = +40°C; SST = -40°C; no liquid sub-cooling; no suction superheat.

Required refrigeration capacity = 100kW.

Table 2: Thermodynamic comparison of inter-stage cooling systems

Type of system	Capacity in kW (TR)	Shaft power in kW	kW output/ kW input (C.O.P.)	Power consumption kW/TR	Saturated intermediate temperature	Compressor RPM
System C	100.24 (28.50)	58.24	1.72115	2.043	-5.8°C	700
System D	104.78 (29.79)	61.72	1.69767	2.072	-6.4°C	750
System A	103.78 (29.508)	76.32	1.3598	2.5864	-8.5°C	850

From *Table 2*, we can observe the following:

i. System C has the maximum C.O.P. and therefore best efficiency.
ii. System C has the lowest power consumption per unit output.
iii. System C has the lowest compressor speed, meaning longer life, less wear and tear.
iv. System C has the highest intermediate pressure and temperature, which means lowest high stage compression ratio, lowest discharge gas temperature at the outlet of high stage cylinders, resulting in better lubricating properties, less overheating and lower inlet gas temperatures to condenser.

Cascade Systems

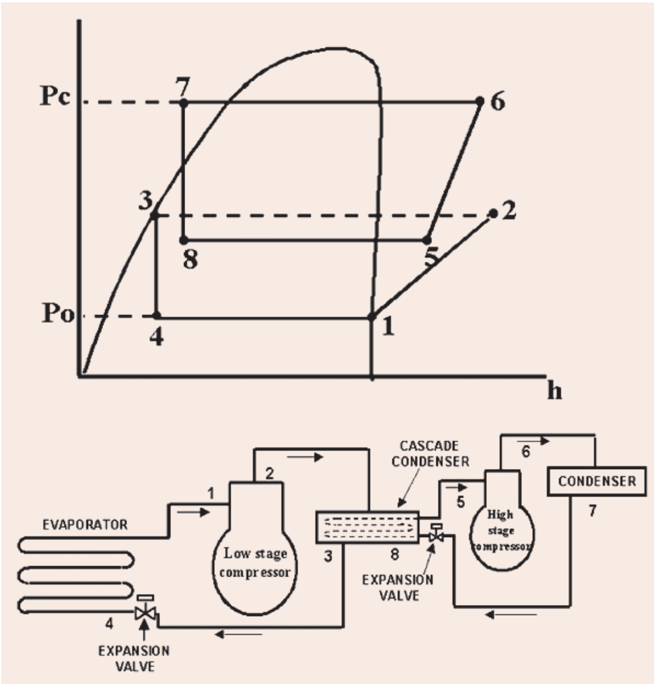


Figure 7: A cascade refrigeration system

For low temperature applications, two independent circuits known as cascade systems are also commonly used.

The high stage circuit is a standard single stage refrigeration unit; however, the evaporator of this unit acts as the condenser for the low stage unit.

The low stage circuit is also a single stage standard refrigeration unit; however, the condenser of the low stage circuit is the evaporator of high stage unit. Thus, heat rejection of low stage is done by the boiling of high stage liquid and in the process the low stage gas gets condensed.

Application Areas

1. Very low temperature applications.
2. Different load patterns for high and low stage.
3. Very high difference between saturated evaporating and condensing temperatures.

Advantages

1. Simplicity of operation.
2. Regular operator can manage the plant.
3. No oil circulation and oil return problems.
4. Three-stage cascade system is also possible.
5. *One can use different refrigerants for high stage and low stage to achieve better results, which is not possible in two-stage single compressor design.* For example, one can use ammonia for high stage and carbon dioxide for low stage. This is not possible in compound two-stage systems as they use the same refrigerant for high and low stage
6. High stage system can function independently without low stage system running, in case temperature requirements are high. This happens many times in cold rooms when very low temperature rooms are not loaded with products.
7. Different design of compressors can be used for high and low stage. One can use reciprocating compressor for high stage and screw compressor for low stage or both the stages with either reciprocating or screw compressors.
8. Load patterns for high stage and low stage can be different. For example, load on high stage could be much higher if the application warrants, and a very small system could be used for low stage if the load requirement is substantially lower. This happens often in a multipurpose cold storage facility when only one small room is used for storing, say, ice cream at -25°C whereas the main facility is used for storing fruits and vegetables at +2°C.

Thus, there is total flexibility available to the system designer if he opts for a cascade system instead of single two-stage compressor selection.

Drawbacks

1. Cascade condenser heat transfer requires temperature differential penalty in the form of increased size and power compared to a two-stage open flash intercooler system.
2. First cost is somewhat higher due to the additional condenser-cum-evaporator, two compressors and two motors.
3. Liquid sub cooling has its limitations.
4. Expansion valves need to be sized for relatively low pressure differentials.
5. Occupies more space and requires engineering and designing skills for vessels, pipe routing, control selection, etc.
6. Quite often the low temperature circuit, using refrigerants like R507, R-23 or carbon dioxide, may have very high pressures at standing conditions and hence a large volume expansion vessel is required to be provided in the system to allow the entire system gas of low stage to expand in the vessel without exceeding allowable pressures.

Two-stage vs. Cascade System

Many consultants and designers of refrigeration systems prefer cascade systems over two-stage systems, claiming that it gives better efficiency. We shall therefore now compare two-stage system vs. cascade system for identical conditions using ammonia refrigerant

Table 3: Thermodynamic comparison of two-stage vs. cascade systems

System type	Compressor Model-RPM	Operating conditions	Capacity in kW(TR)	Power consumption in kW	kW/TR
Booster – low stage	KC4-650 RPM	-30°C/-5°C	100.56 (28.59)	17.36	
High stage	KC3-600 RPM	+40°C/-10°C	128.51	38.34	
Total			100.56 (28.59)	55.7	1.948
Single frame two stage	KC42-650RPM	+40°C/-30°C	101.08 (28.74)	45.82	1.5942

We shall consider operating conditions as +40°C saturated condensing temperature and -30°C saturated suction temperature, and capacity as 100kW at -30°C. For the sake of comparison we shall consider two-stage KC42 compressor so that the cylinder ratio is 2:1 and therefore ideal with system C using open interstage cooling flash cooler.

For the cascade system we shall use KC4 compressor as low stage booster operating at -30°C evaporating and -5°C condensing temperature. For high stage we shall select KC3 single stage 3-cylinder compressor operating at +40°C condensing and -10°C evaporating temperature.

The heat exchanger would have thus 5°C TD (ΔT).

Ammonia-CO_2 Cascade Systems

Since ammonia is generally not used for very low temperatures without encountering vacuum operation (below-33°C), and is not permitted where public may be exposed to ammonia gas leaks, systems using ammonia for high stage remotely located in the plant room and CO_2 as a secondary coolant in the low stage, cooled by ammonia in the high stage, are gaining popularity especially for supermarket applications. This confines ammonia to the machine room, and thus benefits of high thermodynamic efficiency of ammonia may be derived with relatively low refrigerant charge. The volumetric capacity-density of CO_2 being extremely high – nearly 8 times that of ammonia – makes the system compact and competitive to install.

The advantage of such a system is that it is thermodynamically efficient and uses both the natural environmentally friendly refrigerants having zero ODP and GWP.

Conclusion

1. Power consumption per ton is lower with single frame two-stage compressor than with cascade system, because the latter has inefficiency due to additional heat exchanger working as condenser for low stage and evaporator for high stage.
2. Power consumption is nearly 22% higher than two-stage compressor with open flash cooler.
3. A booster high stage cascade system requires in all 7 cylinders of the same swept volume as against 6 for two-stage compressor.

Thermodynamic comparison, however, would not lead to the conclusion that two-stage system is always a better alternative. Designers who have gone for cascade systems have never regretted the choice; it has other obvious advantages that are not possible with two staging, such as easier oil management, simplicity in design, independent circuits, flexibility of compressor types and selection of different refrigerants as well as selecting optimum intermediate pressure and temperature levels.

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Prospects of Powering a Refrigerated Warehouse with Renewable Energy

By Douglas Reindl *Ph.D., P.E., Fellow ASHRAE;* **Marc Claas** *and* **Jake Denison**

Although net zero energy buildings have been successfully demonstrated at residential and small to moderate commercial building scales, they have not been demonstrated for more energy-intensive operations such as food production or large refrigerated storage facilities. The reason is simple: residential and low-rise commercial buildings have the benefit of considerably lower energy use intensity (i.e., annual electric energy required per unit area of the building) when compared to a refrigerated facility.

Figure 1 shows the comparative energy use intensity of various facility types including: a food production facility with refrigerated storage, a health-care facility, a large cold storage warehouse, a commercial office building, and a single-family residential dwelling. The high energy use intensity of a food production facility significantly increases the degree of difficulty and costs for achieving net zero energy performance. One factor that increases the degree of difficulty in implementing sufficient renewable energy production on-site is the large area required to deploy sufficient renewable energy generation to power a food process or refrigerated storage facility. This area is significantly larger than the facility footprint that might use rooftop photovoltaic solar alone.

The analysis presented in this article will show the magnitude of land area required to power such a facility. We also quantify the costs for deploying sufficient renewable energy generation to achieve net zero performance; however, land costs are not included in the economic analysis due to the significant variation in prices based on location.

Refrigerated Facility Overview

The analysis presented in this article is based on an actual refrigerated warehouse comprised of two separate refrigerated docks, a cooler, and three freezers totaling 166,875 ft^2 (15 500 m^2) of conditioned space. The size and respective temperature setpoints for each of the refrigerated spaces in the facility are given in *Table 1,* and the actual metered electrical energy demand and consumption for the facility are used in the analysis that follows. The electrical energy use intensity of this facility is 157 kBtu/ft^2·yr (1,783 MJ/m^2·yr) and it compares well with the "Large Cold Storage Area" energy use intensity shown in *Figure 1.*

In this article, we define a "net zero facility" as one that would be capable of producing at least as much electric energy on-site from renewable sources as it consumes over an annual operating cycle. More specifically, the on-site renewable energy production is sized to annually produce electrical energy equal to the facility electric energy consumption. We assume the facility is grid-connected and the electric utility provides necessary electric power whenever the site electrical demand exceeds the on-site renewable electricity production. We also assume the utility accepts any surplus on-site electricity production during periods when the facility electric demand is less than the renewable energy production. The only constraint applied is that the renewable electric energy production equals the facilities' annual electric energy consumption.

Figure 2 shows the monthly-average daily electrical energy consumption over the annual period from February 2014 through January 2015. The electrical demand for this facility during the summer is 50% greater than the winter. The annual electrical energy consumption for this facility totals 7,717,792 kWh.

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The Challenge of "Net Zero"

Common net zero energy building concepts and their implementation rely on electricity being provided from traditional generation sources (nuclear, natural gas, and coal-fired plants) during periods where the facilities' electric demand exceeds the on-site electric production by renewable sources. Furthermore, most net zero buildings rely on the electric utility to readily receive any excess on-site electricity production during periods when the on-site production exceeds the facility demand.

Although utilities may be able to accommodate this operating strategy today because the penetration of net zero buildings (more broadly, renewable energy production) is low, their continued ability to receive excess electricity production from intermittent renewable energy generation sources with further growth into the future is limited without some means of cost-effectively storing energy. Conceptualize trying to achieve net zero refrigerated facility without being grid-connected – now that is a challenge!

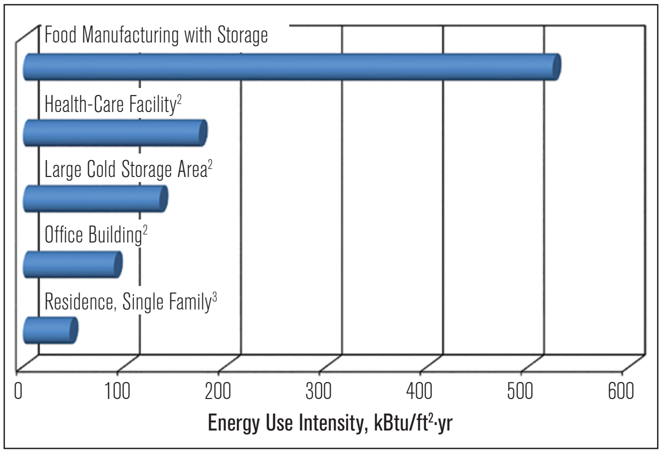

Figure 1: Energy use intensity of various building types

Table 1: Refrigerated space specifications

Space	SetPoint (°F)	Area (ft²)	Height (ft)	Volume (ft³)
Dock 1	32	4,425	28	123,900
Freezer 1	–25	16,000	42	672,000
Dock 2	38	19,800	28	554,400
Cooler 1	35	15,600	42	655,200
Freezer 2	–2	47,050	42	1,976,100
Freezer 3	–20	64,000	42	2,688,000
	Totals:	**166,875**		**6,669,600**

Renewable Energy Technology

Although many renewable energy technologies could meet the electrical energy needs of this refrigerated facility, we are limiting the analysis to photovoltaics (PV), wind, and a hybrid system consisting of a combination of PV and wind energy generation. Both PV and wind energy technologies have been widely implemented at the utility-scale sizes consistent with the generation required for enabling this refrigerated warehouse facility to achieve net zero energy performance.

The analysis of renewable energy options for this facility was simulated using the System Advisor Model (SAM) software package.[1] SAM allows users to simulate the energy and economic performance of various renewable energy technologies for a given location. The simulations performed with SAM aim to determine the necessary sizes and capital costs for renewable energy systems to produce sufficient delivered electrical energy equal to or greater than the actual required annual electrical energy for the facility (7,717,792 kWh). As noted in the "Challenge of Net Zero" sidebar, a critical assumption in this analysis is the utility grid will freely "supply" needed electricity during periods of on-site under-generation and "credit" the facility during periods where the renewable electricity generation exceeds instantaneous electrical demand by the facility. The renewable energy generation is sized so that, on an annual basis, the net-metered electricity for the facility is zero.

Simulation Parameters

One of the measures of performance included in the analysis is the "levelized cost of electricity" (LCOE) that represents the average cost of electricity (kWh) generated by the renewable energy system over an assumed 25-year life-cycle, adjusted for inflation. SAM calculates LCOE as follows:

$$LCOE = \frac{C_{AfterTax,n} + \frac{\sum_{i=1}^{n} C_{AfterTax,n}}{\left(1+d_{nom}\right)^{n}}}{\sum_{i=1}^{n} \frac{Q_n}{\left(1+d_{real}\right)^{n}}}$$

where

η = 25 years

$C_{AfterTax,n}$ = cash flow after taxes in year n [$]

d_{real} = 0.082

Q_n = 0.025

$d_{nom} = (1+d_{real})(1+e)$

The variable d_{nom} represents the nominal discount rate and d_{real} represents the real discount rate. The parameter *e* is the inflation rate assumed at 2.5%. Since the nominal discount rates vary, the LCOE results are shown parametrically for discount rates of 2%, 4%, and 6%. The default system pricing data in SAM were used for this analysis, and the price of land was not included due to wide variations in real estate values and the relatively small impact that land acquisition will have on total installation cost.[4]

In addition to the above-mentioned economic parameters, location information and the associated estimates of resources

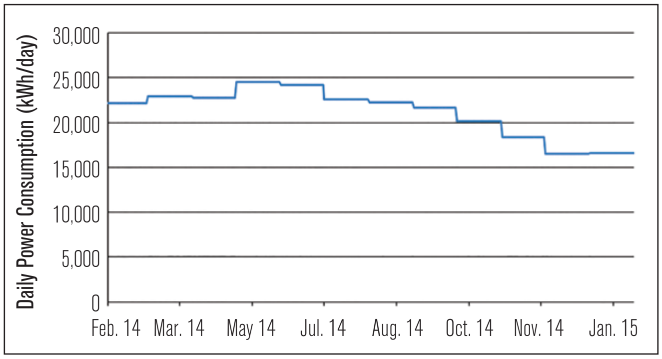

Figure 2: Monthly-average daily electric energy consumption for the refrigerated warehouse during a one-year period ending January 2015

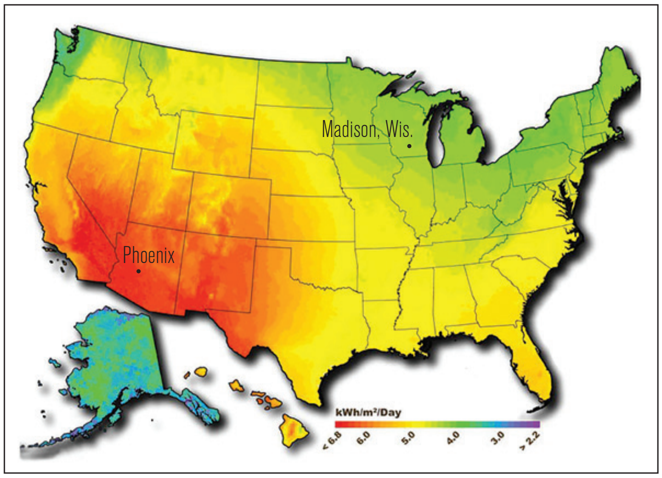

Figure 3: PV resource map for the United States[5]

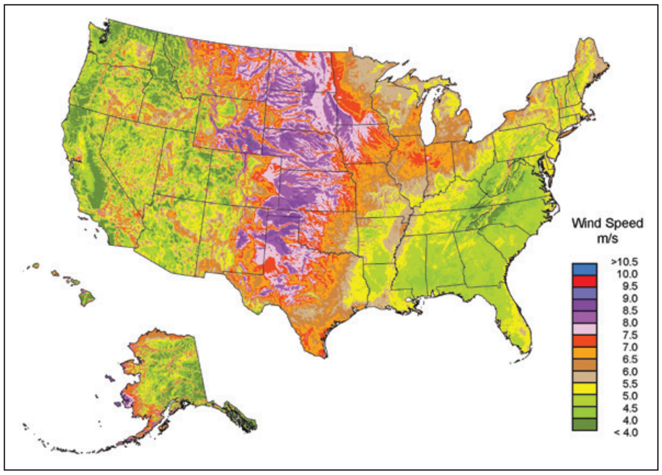

Figure 4: Wind energy (at 265.5 ft elevation) resource map for the United States[6]

(incident solar radiation) are required. Typical Meteorological Year (TMY) data is used in the PV analysis and two different locations: Madison, Wis., and Phoenix are evaluated. *Figure 3* shows the distribution of PV resource for the United States, noting more resource availability for PV in Phoenix compared to Madison. This resource variability creates further economic differences between locations. *Figure 4* shows wind energy resource availability for the United States at an elevation of 262.5 ft (80 m).[6]

Net Zero With Photovoltaic

The PV technology assumed in the present analysis are PV module(s) with inverters. The PV modules considered here are among the most mature and studied PV technology: monocrystalline silicon. Fixed mount arrays with a slope of 33° were chosen for both locations. The degradation rate characteristics for this PV technology are well known and assumed to average 0.4% per year.[7] We assume the power inverters are sufficiently large as to avoid "clipping" the generated dc power; thereby, avoiding any "wasting" of electricity generated by the PV modules.

PV Results for Madison, Wisconsin

For the Madison location, a PV system comprised of 18,669 solar modules with 19 power inverters capable of producing 5,700 kW_{dc} is required to meet the annual electrical energy needs for the refrigerated warehouse. Key results for the net zero PV system in Madison are shown below in *Table 2*. The 7,834 MWh of annual electrical energy generated by the PV system is just slightly greater than the actual facility requirement of 7,717 MWh. The capital cost of the system is estimated at $9.1 million and the installation would require 25.1 acres (10.2 ha) of suitable real estate to adequately site. The capacity factor of 15.7% for this case represents the ratio of the actual electrical energy produced by the PV system to the electrical energy the PV system could produce if it operated at its rated capacity throughout the entire year. *Table 2* shows the levelized cost of electricity (LCOE) for the

Table 2: Madison, Wis., net zero PV results and levelized cost of electricity (LCOE)

Results			
Annual Energy Generated (kWh)	Installed Cost ($)	Capacity Factor (%)	Land Area (acres)
7,834,734	9,133,249	15.7	25.1
LCOE With Varying Nominal Discount Rates			
	Discount Rate (%)		Nominal LCOE (¢/kWh)
	2		11.49
	4		11.68
	6		11.68

Table 3: Phoenix net zero PV results and LCOE

Results			
Annual Energy Generated (kWh)	Installed Cost ($)	Capacity Factor (%)	Land Area (acres)
7,838,937	6,852,295	21.3	18.5
LCOE With Varying Nominal Discount Rates			
Discount Rate (%)		Nominal LCOE (¢/kWh)	
2		8.55	
4		8.69	
6		8.85	

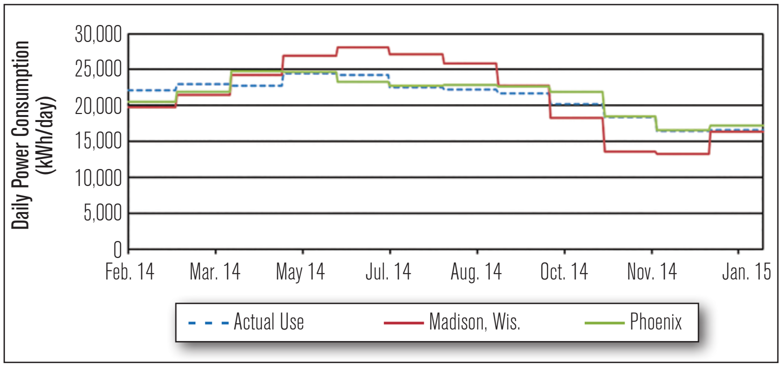

Figure 5: Actual monthly-average daily facility electrical energy consumption along with the predicted monthly-average daily electricity generated by the PV system to achieve net zero performance for both Madison and Phoenix

PV system in Madison over a range of discount rates. For the 2% discount rate, the average cost of electricity for the 25-year life is 11.49 cents per kWh.

PV Results for Phoenix

For the same PV technology applied to a similar facility located in Phoenix, the greater solar resource there allows the system size to decrease to 13,755 modules with a nominal capacity of 4,200 kWdc along with 14 inverters to meet the annual electricity requirement.

Table 3 shows the key results for Phoenix. The capital cost in this case is just under $7 million and the required land area to site the PV system decreases to 18.5 acres (7.5 ha). The greater solar resource in Phoenix also translates into a higher capacity factor of 21.3%.

Table 3 also shows the LCOE over the same range of discount rates as considered for Madison. Because the annual electrical power for the facility can be met with a smaller solar system, the LCOE is less than the Madison case. At a 2% discount rate, the LCOE is a competitive 8.55 cents per kWh.

Figure 5 shows the monthly-average daily electrical energy consumption for the facility and the PV production on the same basis for both the Madison and Phoenix locations. The greater solar resource in Phoenix is evident in the ability of the PV-produced electricity to more closely track the actual facility demand on a monthly average basis.

Net Zero With Wind Energy

When selecting wind turbines, it is essential for the equipment operating profile to match the characteristics of the wind resource expected at the location of interest. The wind turbines in both locations are utility-scale machines with 262.5 ft (80 m) hub heights. The land requirement to support the wind energy generation option is larger than the PV system because of the required fall radius. The fall radius represents the spacing between each of the wind turbines such that potential energy loss of downwind turbines from upwind shadowing is mitigated. NREL recommends a minimum fall radius of five to 10 rotor diameters to optimize energy production.[8] The results for the wind turbine options below are based on a fall radius of eight rotor diameters.

Wind Results for Madison

The wind energy generation option for Madison consists of four turbines, each with a rating of 750 kW.

Table 4: Madison, Wis., net zero wind energy-based results and LCOE

Results			
Annual Energy Generated (kWh)	Installed Cost ($)	Capacity Factor (%)	Land Area (Acres)
8,370,403	19,141,380	31.9	66.7
LCOE With Varying Nominal Discount Rates			
Discount Rate (%)		Nominal LCOE (¢/kWh)	
2		21.15	
4		21.78	
6		22.45	

Table 5: Phoenix net zero wind energy-based results and LCOE

Results			
Annual Energy Generated (kWh)	Installed Cost ($)	Capacity Factor (%)	Land Area (Acres)
8,529,605	45,393,908	13.5	218.9
LCOE With Varying Nominal Discount Rates			
Discount Rate (%)		Nominal LCOE (¢/kWh)	
2		51.84	
4		53.26	
6		54.73	

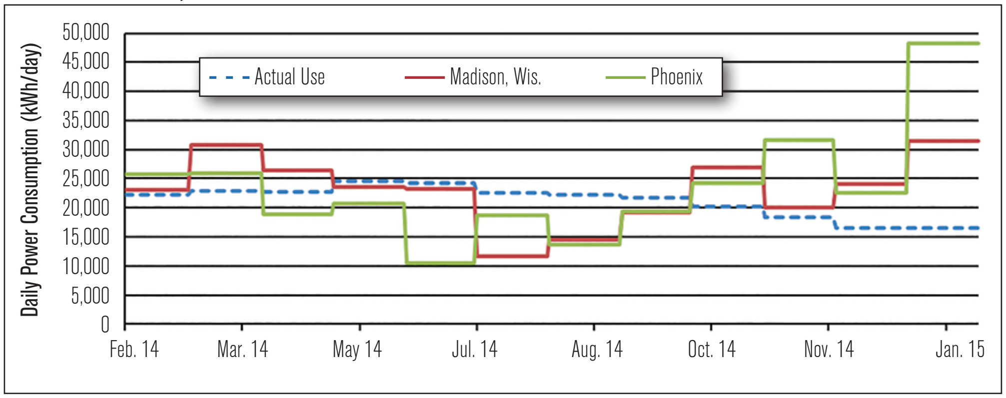

Figure 6: Actual monthly average daily facility electrical energy consumption along with the generated electricity for wind to achieve net zero

Interestingly, the wind resource in Madison is sufficient to produce a capacity factor of nearly 32%. Key results for the net zero wind system in Madison are shown in *Table 4*. The installed cost of the wind energy option is $19.1 million, significantly higher than the PV option. The higher capital cost leads to a marked increase in the life-cycle cost of electricity (also in *Table 4*). For comparison to PV, the average cost of electricity for the 25-year life is 21.15 cents per kWh for the 2% discount rate.

Wind Results for Phoenix

The wind turbine analysis in Phoenix uses 12 turbines with a 600 kW rating each. Wind energy in Phoenix struggled to meet annual electricity requirements for the facility, resulting in a capital cost of more than twice that of a similar setup in Madison and six times more than the PV system in this same location. The high capital cost is a result of comparatively poor wind resource in Phoenix as expected based on the wind resource shown in *Figure 4*. This low wind resource results in large required siting area footprint and a lower capacity factor shown in *Table 5*. This table also shows the LCOE over the same range of discount rates as considered for Madison.

When considering wind turbine power production, both locations struggled during the hottest months of the year, when facility electrical demand peaks, as evidenced by reviewing the results shown in *Figure 6* This mismatch of facility demand and on-site renewable energy production puts added stress on the electric utility since they are relied upon to bridge the gap between facility demand and comparatively poor renewable energy system output.

Figure 7 shows the monthly-average daily electric energy required for the refrigerated facility along with the monthly-average daily electricity generated by PV and wind. During summer months, the production of electricity by PV is high while the wind energy is low. The opposite occurs during the wintertime, suggesting the potential for synergy between PV and wind resources. The "hybrid" system arrangement combines the two energy generation methods to evaluate how each complement the other.

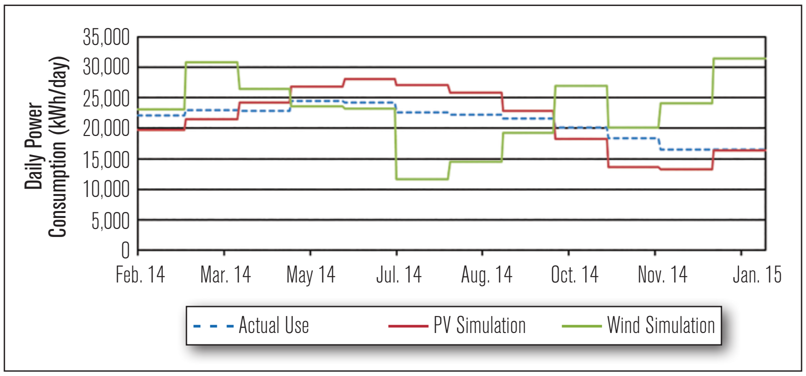

Figure 7: Actual monthly-average daily facility electrical energy consumption along with the generated electricity for PV and wind-energy systems to achieve net zero

Table 6: Madison, Wis., net zero hybrid power results and LCOE

Results			
Annual Energy Generated (kWh)	Installed Cost ($)	Capacity Factor (%)	Land Area (Acres)
7,950,290	11,716,320	18.9	19
LCOE With Varying Discount Rates			
Discount Rate (%)		Nominal LCOE (¢/kWh)	
2		16.85	
4		17.14	
6		17.44	

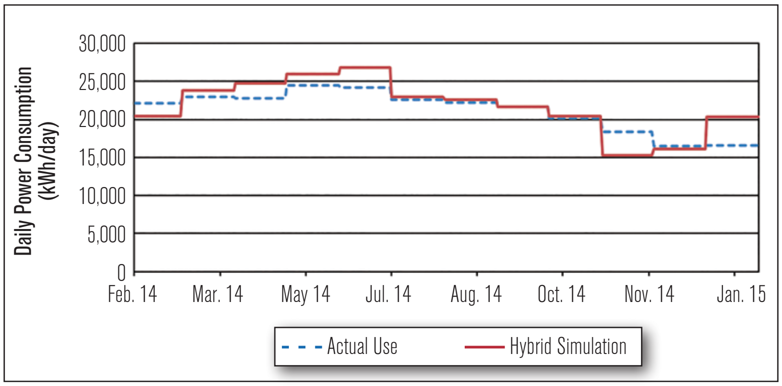

Figure 8: Simulated power generation using hybrid design compared to actual facility demand in Madison

Hybrid Renewable Energy System Results for Madison

Based on the PV simulation results, the refrigerated facility located in Madison would benefit from supplemental energy generation during the winter months when the day length is short and the solar resource comparatively low. A combined PV-wind turbine case is evaluated where most of the power generation is derived from the PV modules, as they were capable of generating most of the electrical demand year-round. The same PV modules and inverters were selected, but the PV system design was scaled back. The PV system was designed to generate 4,000 kW_{dc}, translating to 13,104 modules. This part of the on-site electricity generation requires 17.6 acres (7.1 ha) of land to install. The design of the wind energy generation system includes one turbine with a nameplate capacity of 810 kW. This single wind turbine only requires enough land to satisfy required offsets. Using the same weather data and economic parameters, the simulation shows the installed cost is about 28% higher than the cost of only installing PV panels, but this arrangement provides added reliability with two renewable energy generation sources available. All relevant parameters for the hybrid power generation simulation located in Madison are summarized in *Table 6*. The addition of wind energy production enabled an increase in the capacity factor compared to PV-alone; however, the increased system cost translates into a higher overall LCOE, as also shown in *Table 6*.

Figure 8 shows the hybrid power generation system design discussed above creates an annual trend that is much more in phase with the actual demand of the facility. The maximum rate of energy deficit with the hybrid system is only 3,090 kWh/day, compared to 4,780 kWh/day with the PV system, and 10,460 kWh/day with the wind turbine system.

Hybrid Renewable Energy System Results for Phoenix

The hybrid system design for Phoenix emphasized PV power generation due to the greater solar resource there with supplemental energy derived from wind turbines to produce more reliable time-dependent power generation. This specific design uses one wind turbine, coupled with 11,788 PV modules and 12 power inverters. *Table 7* summarizes the hybrid system characteristics in Phoenix, and it shows that the cost of this system is higher than the PV-only system.

Figure 8 depicts the performance of the hybrid system. Despite varying weather throughout the year, the rate of electricity production remains fairly constant but is still not as consistent as PV alone in the Phoenix location. Although analysis of hybrid designs can vary widely depending on the percentage of electricity that originates from either the PV system or the wind turbines, the hybrid system for Phoenix had a greater power production deficit than the PV only system due to the poor wind resource in this climate/location. The maximum daily electrical deficit of the PV system in Phoenix is 1,620 kWh, compared with 2,430 kWh for the hybrid system consisting of only one wind turbine.

The wind resource in Phoenix is simply not large enough to gain any appreciable advantage when considering the large capital cost required to purchase and install wind turbines in that location. Coincidentally, the solar resource in Phoenix is not only high, but consistent, so PV solar becomes the preferred option.

Table 7: Phoenix net zero hybrid power results and LCOE

Results			
Annual Energy Generated (kWh)	Installed Cost ($)	Capacity Factor (%)	Land Area (Acres)
7,934,221	11,658,626	20.1	18
LCOE With Varying Discount Rates			
Discount Rate (%)		Nominal LCOE (¢/kWh)	
2		16.65	
4		16.94	
6		17.24	

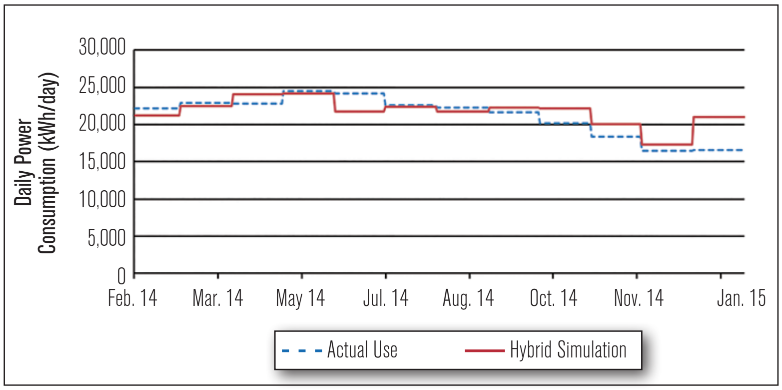

Figure 9: Simulated power generation using hybrid design compared to actual facility demand in Phoenix

Conclusions & Next Renewable Consideration

The use of a photovoltaics, wind, and a combination of the two offers the theoretical potential to achieve a net zero refrigerated warehouse. The electric data used as a basis for sizing the systems is taken from an actual operating facility and applied in the present analysis to two locations: Madison, Wis., and Phoenix. In reality, the electrical energy use profiles for two equally sized facilities would vary between these locations but maintaining a consistent electricity demand for the facility, independent of the location, allowed assessment of the comparative renewable energy resource.

The analysis shows that PV can be used to achieve net zero at a LCOE of approximately 11.5 cents per kWh in Madison and 8.6 cents per kWh in Phoenix. Wind energy generation yielded a LCOE of approximately 21.2 cents per kWh in Madison and 51.8 cents per kWh in Phoenix. The high cost for Phoenix is reflective of the relatively poor wind resource available in that location. A PV+wind energy generation hybrid was also analyzed and the LCOE yielded 16.9 cents per kWh in Madison and 16.7 cents per kWh in Phoenix. These results also show that all considered systems rely on grid-connected electricity since there are significant periods when the facility electric demand exceeds the PV system electric production and vice versa. We also need to emphasize that the economic results presented in this article do not consider the cost of land for siting the renewable energy production and associated land-use planning issues. Both of these are significant and highly variable depending on the specific siting of the facility and its renewable energy generation. As a result, the LCOE values provided in this paper should be considered as optimistic.

Based on the size and production profiles of the energy systems required in this analysis, it is clear that any real attempt at a net zero refrigerated warehouse would require maximum efficiency improvements coupled with refrigeration load shifting, electrical storage, and other creative solutions. What these solutions look like will require more detailed analysis to find the optimal balance between loads and electrical production.

What Would It Take to Go "Off The Grid"?

Large-scale penetration of electric generation from intermittent renewable sources becomes far more realistic with some form of energy storage. Energy planners and technologies have focused on electrical storage technologies as a means of bridging mismatches in end-use electricity demand and renewable electricity production. The table below shows the amount of battery capacity that would be required to absorb the mismatch between electrical generation and consumption for each simulation presented here.

Minimum Battery Storage (MWh)

	Madison, Wis.	Phoenix
PV	310	80
Wind	700	1,100
Hybrid	110	85

Because the solar resource in Phoenix is the most consistent, it has the smallest battery storage requirement. The hybrid system in Madison is a close second with far less battery storage required compared with either wind or PV alone.

Although battery technologies are continuing to evolve and improve, their costs are high. Another alternative would be to use thermal energy storage rather than electric energy storage. ASHRAE's recently completed research project, RP-1607, found that thermal energy storage is currently the most cost-effective means to enable greater renewable energy generation deployment. Considering that a refrigerated warehouse, inherently, has stored product that can potentially be used as a thermal storage medium, shifting the electric energy consumption for a refrigerated facility can be accomplished at low to no capital cost increase. Load-shifting using stored product can help reduce the reliance on the electric grid to bridge mismatches in electricity production and demand.

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Reefers and cold stores are vital links in the cold chain

India Cold Chain Performance Issues: Investor Realities

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This article was first published in the March-April 2015 issue of Cold Chain. In view of the spate of investments taking place and expected in the near future in the cold chain sector in India, this article is even more relevant today.

The Cold Chain Business - an Attractive Opportunity

Market Demand Is Appealing

Cold chain logistics spend in India is reported to be US$2.5-2.7 billion, growing to US$4.5-8 billion by 2017 and expanding 15%-20% p.a. According to National Centre for Cold-chain Development (NCCD), the food industry is estimated at US$235 billion with a 10% CAGR, but farmers still suffer from minimal margins, primarily due to a post harvest loss in value of perishable produce at an estimated US$16.7 billion. There is a serious need for more integrated pack houses and refrigerated transport to help offset this loss, not just more cold stores.

These market numbers and the fast rising demand for quality processed foods, makes it seemingly worthwhile for cold chain investors to buy in on a viable business case. However, it is recommended that one drill down into the supporting data first to:

1. Confirm if the supporting data is accurate and representative
2. Understand and agree with the key market potential assumptions
3. Gauge core industry obstacles and their impact on a start up
4. Validate the solutions available that reliably deal with these obstacles
5. Determine if you can reach expected performance levels despite the challenges.

On paper, it is not difficult to model a cold chain set up and show a 5-6 year ROI, 18%-21% IRR, low CAPEX and controlled OPEX for a decent bottom line, and you can do that without comprising on the quality of the facility or equipment installed. That is an attractive performance picture. However, in reality, can:

1. The end product still be affordable to the target market?
2. Project planning be executed successfully?
3. The operator find skilled management and labour and train them to professionally manage a modern and seamlessly linked cold chain?
4. The promoter deal with any and all of the expected implementation challenges along the way, starting with

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land acquisition and contouring and then detailed vendor management including, but not limited to:

a. Civil work, PEB sourcing and erection
b. Material and equipment sourcing, delivery and installation
c. BOM timeliness, quality and cost control
d. Fire and safely
e. Electrical, plumbing work
f. Project management cost, time and quality control

Bear in Mind, it is about Protecting Value

The investor needs to consider a myriad of strategic and day-to-day planning and operating components, each having its own complexity. The need to create 'end-to-end' cold chain temperature control integrity and market reach that covers reliable, timely and lowest landed cost for farm to store deliveries elevates the complexity.

It is important to first determine if you are aiming to protect the value of the low volume, higher value, processed chilled and frozen products or will it be the high volume, lower value fruits and vegetables sector? Each of these two categories requires its own independent market assessment, and tailored cold chain set ups configured to specific product requirements.

In either of the above two market categories, cold chain operations cannot perform, be efficient and deliver value with weak or missing links. So it is important to step back and remember that a valid cold chain operation is not about storage or transport, it is about protecting two types of value: 1) product and 2) stakeholders' ROI (see *Figure 1*). This objective requires cost controls for end product affordability, continuous product quality assurance and start to finish value addition management. These particular process controls apply whether they are for cold store and reefer transport set up or for carrying out live buy, sell, transport, store and distribute operations post project commissioning.

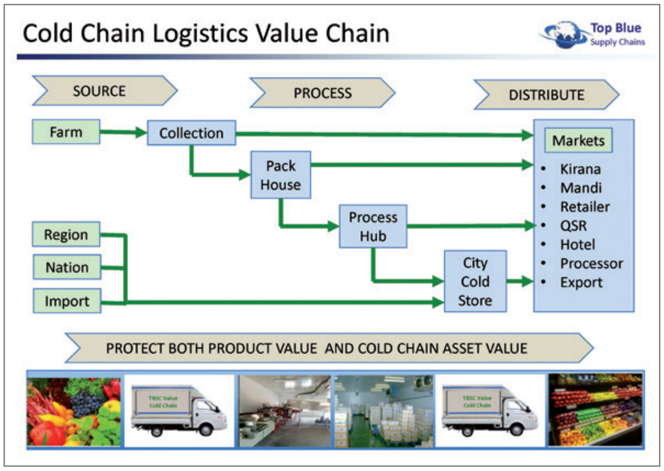

Figure 1: Cold chain logistics value chain

What Level of Integration Works?

As regards affordability and value, integrated refrigerated storage and transportation is essential, and the key word is 'integrated'. This requirement is closely followed by the need for each cold chain transaction participant to benefit in order for the business to be sustainable, and that is only going to happen if you wisely integrate operations to speed goods to the market and extract waste from the cold chain. In reality, the vast majority of India's cold chain set ups are not integrated; they are heavily focused on cold stores only and typically, silo-type operations that may, or may not, allow collaboration and synchronization on some, or all, of perishable product shipment hand offs. A viable cold chain must permit links, product track and trace, cost and service quality controls and inherent efficiencies (see *Figure 2*).

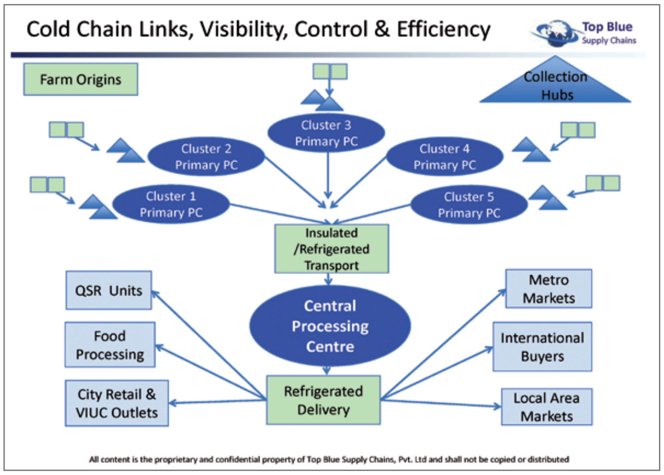

Figure 2: Cold chain links, visibility, control and efficiency

Multiple Party Benefit also Requires a Collaborated Solution

Cold chain industry realities dictate addressing what I like to call the 'bigger business picture'. Concentrating a cold chain solution effort on just one element or player in the picture does not complete the puzzle. It is recommended that a demand planning approach to solution design embrace 1) buyer, 2) seller and 3) logistics provider for accurate big picture assessment of the necessary components, functionality, size and budget for a specific cold chain operation. A recommended procedure would be to:

1. Firm the retailer (buyer) requirements
2. Compare that consumption demand with production (seller) capability
3. Design a cold chain solution with the required services
4. Identify the appropriate mix of cold chain logistics services and providers
5. Take the complete cold chain solution back to the buyer for approval
6. Implement the project to control costs and protect the two primary values.

Validating Demand for Cold Chain Services

A Thorough Market Assessment Is Essential

Once the India cold chain investor has a basic understanding of the set up realities, focus should be on validating market demand. It is recommended that a very detailed market segmentation and analysis be conducted in two, back-to-back study activities: *Top-down Market Objectives*, to then be validated by *Bottom-up Client*

Confirmations. The purpose of the two-part study is to validate the business case and a thorough market assessment will be a light at the end of the tunnel for the wary cold chain investor.

If prepared correctly, strategic cold chain investment recommendations, based on a quality market study, can be both sound and persuasive. The only way to secure the soundness is to be product-specific and undertake the harder task of secondary market analysis, speaking directly with all the cold chain participants for current and accurate input. The only way to be persuasive is to present the facts in a solid business case.

High End Chill and Frozen Gets a Lot of Attention

Primary market intelligence tells us that dairy, marine, poultry, Temperature Controlled Logistics (TCL), pharmaceutical and other non-horticulture industry cold chains have been receiving heavy investor attention resulting in a whirl of activity to improve the quality of packaged, RTE (Ready-to-Eat) and RTC (Ready-to-Cook) products, but NCCD will opine that there is a huge difference between cold chains for horticulture products and the food processing industry.

However, investors should also look at the bigger need for eliminating India's huge loss of post harvest produce value and give it due consideration. Given today's modern equipment and technology, there is good potential for better economics from hybrid cold and dry chain solutions across common assets. It is feasible to manage multiple types of perishable product under the same roof, in the same or separate chambers and even in the same vehicle; however, this is limited by product compatibility and the constraints need to be clearly understood. With the right attention to efficiency across the cold chain and some smart and selective value-add grading, it is also feasible to make a higher profit cleaning, packaging and cooling fresh fruits and vegetables.

On the Surface, Primary Market Intelligence Supports New Cold Chain Investment

1. There is a growing consensus across private industry that there is a real and increasing demand for faster delivery of more, higher quality and a greater variety of, perishable products.
2. However, India's middle and upper classes do not constitute the majority of the consumers, and traditional buying behavior prefers seasonal products straight from the ground. Thus discard 60% of the horticulture produce that goes direct to rural shops or terminal markets, and concentrate on the balance.
3. That balance according to *Business Line*, 3 March 2015, only receives 10% of the refrigeration services required, and hence the waste in value terms.
4. So it could be concluded that around 30% of the perishable production is the target for new cold chain services and by today's estimates, this could translate into 30% of, say, 280 million metric tons, representing a considerable potential. It is estimated that this segment needs an additional 30-35 million metric tons of cold storage and, according to NCCD, as many as 60,000 refrigerated vehicles.
5. The bottom line is that there is a significant tonnage gap between the amount of products needing refrigeration and today's refrigeration service capacity.

Government Support Continues to Increase

Another boost to investor confidence is that this estimated 80-90 million metric tons of produce is not going unnoticed by the Central Government and the States. There are already attractive subsidies in place to support horticulture production growth and cold chain development. As seen by the recent approval of 17 new Mega Food Parks for a total of 42, representing an increase in funding of Rs.6,000 Cr, there is a Government commitment for financial support to the food processing industry that will create more value for growers, make more affordable products available for all and help increase India's horticulture yield, diversity, product quality and produce value.

Modern QSR and Food Retail Is on the Rise

India's busy middle class consumers, especially in metros with higher purchasing power, are buying more prepared fruits and vegetables and processed foods either direct from stores or while dining out at QSRs, restaurants and hotels. Investments are being made to meet that demand, which in turn helps us substantiate the overall need for more modern cold chains. Some trends:

1. *Business Line*, 13 February 2015, reported that cold chain warehousing is to take up 3-4 million square feet by end of this year.
2. A leader in cold chain logistics has built their infrastructure steadily, across India, to 25 warehouses and 500 vehicles, have a CAPEX of Rs 110 Cr per year that will add 25,000 pallets per year, and are targeting over 100,000 pallet positions.
3. A fast rising online food firm proudly raised US$60 Million and announced earlier this month (*Business Line*, 5 March 2015) that they have 4.5 lakh customers, an average 8,000 orders per day with expectations to hit 12,000 on peaks days in April, and are expanding into cut vegetables and RTC.
4. A recent article in the *Business Line* covered a mobile green grocer movement as filling in the gap created by consumer demand for quality not being met by traditional food retailers. Reportedly, this firm is becoming a leader in competing with supply chain excellence, not price, and doing so through an eco-system of partners. They buy from known sources that have known quality and arm mobile carts with blue-tooth printers and GPS in order to deliver pre-priced, packaged fresh organic produce direct to Bangalore consumers with the cold chain replenishment properly governed by Point of Sale (POS) data. They are taking advantage of the estimate that 90% of India's F&V market is unorganized and can successfully sell at 15%-20% higher than local F&V markets.
5. According to *Business Line*, 19 March 2015, an existing e-commerce provider sells organic produce online. It went on to state that since prices can escalate 100% or more from farm to market and the growing concern of India's middle class about food contamination, the take-up of higher quality organic produce is happening and, according to their MD, organic production can reduce food arbitrage by 30%.

In short, there is a lot of cold chain investment activity happening, ranging from organic farms and small mobile carts to mega food parks.

The Blunt Truth about Cold Chain Industry

If you have been thinking that this article is painting a bit too much of a 'rosy' investment picture, let us look at some additional market realities and challenges that must be recognized and considered as it regards the 'what', 'where', 'how' and 'how much' for a cold chain investment.

Statistics Validity Issue

While we see a lot of statistics being published on regular bases by the Centre, states and industry organizations, there is a problem taking these numbers at face value. Most are somewhat dated, incomplete and at too high a level for a business case and to justify an investment. Hence the recommendation for the two-part market study as the first step.

Common Management Challenges

While each cold chain set up will have its own set of conditions, some common challenges awaiting cold chain entrants include:

a. Less than satisfactory cold chain critical mass for suitable return on investment in a specific area.
b. High cost and unreliable power supply impacting cold storage operating costs and quality controls. The adoption of renewable energy sources in the cold chain has been slow.
c. There is a need for 'right-sized' temperature controlled logistics assets closer to the farms and beneficial to clusters. The value goes up the sooner produce maturing is arrested.
d. In most sectors there are large gaps with production volumes exceeding available cold storage capacity; however, there are also areas where capacity exceeds demand and this could be in the range of 30% to 50%.
e. Managing turnkey or complete Project Management Consulting (PMC) projects can be demanding and takes careful project management planning and execution with attention to detail, especially vendor management, labour management and engineering drawing iterations.
f. There is a lack of professional understanding regarding cold chain requirements. For example, spending heavily on cold storage facilities and refrigerated vehicles, but not outfitting the operation with proper business management systems and SCM IT to track results.
g. A lack of management, supervisory and labour skill exists and delivering reliable day-to-day quality and cold chain efficiency becomes a challenge.
h. Farm production varies in type, volume and quality making sourcing predictability difficult.
i. Not paying adequate attention to raw material sourcing and inclusion of farmers and Farmer Production Organizations (FPOs) leads to inadequate product flow and lower quality of out-turn.
j. Although improving, obtaining Government subsidy support can be a challenge and takes time to manage varying processes
k. Transplanting western cold chain practices as is, does not work well and a shortage of complete, 'end-to-end' cold chain success stories makes it difficult to determine India's best practices.
l. There is a lack of hybrid, multi-industry asset sharing set ups that demonstrate how to leverage land, building, machinery, technology, power and labour costs.
m. High-end cold storage and food processing machinery is typically foreign and costly.
n. Producing perishable product to meet export food and safety standards is difficult unless you control the entire production to market processes.
o. Incomplete pan-India cold chains prevent proper distribution of production surplus to consumption gaps:
   - India's long distance refrigeration transport is incomplete as regards the geography covered and full trip temperature control.
   - Small truckers with depreciated vehicles undercut freight rates, making it difficult for new operators to run modern vehicles with skilled drivers.
   - New reefer operators must train skilled drivers or double up the driver team to ensure protection of product value.
p. Knowing the market challenges prepares the investor for what is needed to protect perishable product value. *Figure 3* depicts some fundamental expertise needed for fruits and vegetables.

Figure 3: Farm to cold store to outlet – expertise required

Planning and Operating Disciplines

Cold chain performance realities make it difficult to manage for optimum bottom line results. Promoters must enter with a strong commitment to project management quality and cold chain operating precision that drives the needed system efficiencies and creates maximum product value.

A Cold Chain Performance Check List

Bearing in mind that there are no short cuts, some key cold chain performance enablers include:

1. CAPEX and OPEX
2. Geographic reach
3. Operating scalability
4. Energy savings

5. Asset leverage
6. Supply Chain Management – Information Technology (SCM IT) collaboration, control and visibility
7. Implementation of Standard Operating Procedures (SOPs)
8. Skills training
9. Plant layout
10. Plant efficiency
11. Right-sized chambers
12. Quality refrigeration equipment
13. Quality insulation (warehouse and vehicles)
14. Right-sized collection infra-structure
15. Sourcing relationships (backward market links)
16. Buyer relationships (forward market links)
17. Vehicle load and route planning

Planning Your Cold Chain

When designing cold chains, it is suggested to seek out any missing expertise that is not readily available in-house for both design and project execution. It should also be kept in mind that the project objectives are to produce a cold chain that protects product quality, maximizing value with fastest possible, on-time delivery by the most economical means.

Figure 4: Taking total project management responsibility

Figure 5: Using effective project management controls

To achieve this level of project management performance, it is recommended to commit to some fundamental project responsibilities and use effective project controls to ensure expected results (see *Figure 4* and *5*).

Running Your Cold Chain Operations

Assume that cold store facilities and refrigerated vehicles will come with the necessary plant and vehicle based refrigeration system technology to control and monitor temperature and environments. Monitoring would be with central (control room) computers, chamber location and truck cab displays.

Also there is a wide variety of portable temperature, relative humidity and GPS monitoring and data recording devices and sensors available that can be positioned in fixed locations, e.g. chambers, or in vehicles while in transit. These devices enable auditable event tracking records, shipment track and trace status and pro-active variance alerts to trigger preventive measures and minimize disruptions.

Skills Training

As will all precision oriented operations, skills training is a critical component for cold chain performance. This includes the need for cold storage warehouse, logistics management and vehicle operators to be certified on their tasks, and also includes having suppliers, buyers and third party solution providers on board with predicable skills (see *Figure 6*).

Everyone on the team then needs to be committed to following their task specific SOPs and using IT systems accordingly. Two training fundaments should be, attention to 'what' and 'why'. *What* covers the worker's day-to-day tasks, and *Why* lets the workers understand the relevance of their work.

Figure 6: Training for assured solution quality

The Need for Cold Chain IT

A central data collection platform can take in electronic input from multiple fixed locations and vehicles, sort that data and generate event status updates and pro-active alerts, should there be unacceptable changes in temperature or humidity or vehicle position, at any given time. Some fundamentals to consider for cold chain (SCM IT) include:

1. Operating the cold store and reefer transportation network will require IT systems that support visibility and data capture of end-to-end activities, namely, 1) inbound to warehouse, 2) within warehouse and 3) destination dispatch.
2. Enterprise Resource Planning (ERP) or basic Order Management Systems (OMS) can be readily integrated with today's cloud based SCM IT, Transportation Management Systems (TMS) and Warehouse Management Systems (WMS) applications to manage events, collect financial information, receive shipment bookings, create the most economical consolidations, rate and route shipments, track and trace orders and auto-generate shipping documentation and MIS reports.
3. Assuming the investor is seeking full value, a complete cold chain operation will be both complex and comprehensive and require tight SOPs and systems to regulate and, where feasible, automate processes. As such, SCM IT, enhanced for perishable product 'end-to-end' workflow and temperature and humidity control measurement, is essential in order to electronically capture and present all relevant data, status alerts, events and especially event exceptions, during the perishable product life cycle. In other words, provide management with near-real time visibility and MIS for best possible planning and decision-making.
4. Fully protecting product value is not simply a function of the refrigeration systems, it also requires temperature control logistics practices at each and every step of the cold chain movement. This should start at the farm and end when the buyer picks up the merchandise. Some important SCM IT functions for protecting perishable products up to store delivery are shown in *Figure 7*.

Figure 7: On-line cold chain product value management

To support this monitoring, it is important to understand the need for a collaborative platform that allows all the key cold chain players, viz. farmer to retailer, to participate in the input and viewing of near-real time data. A typical IT architecture for supply chain collaboration is depicted in *Figure 8*.

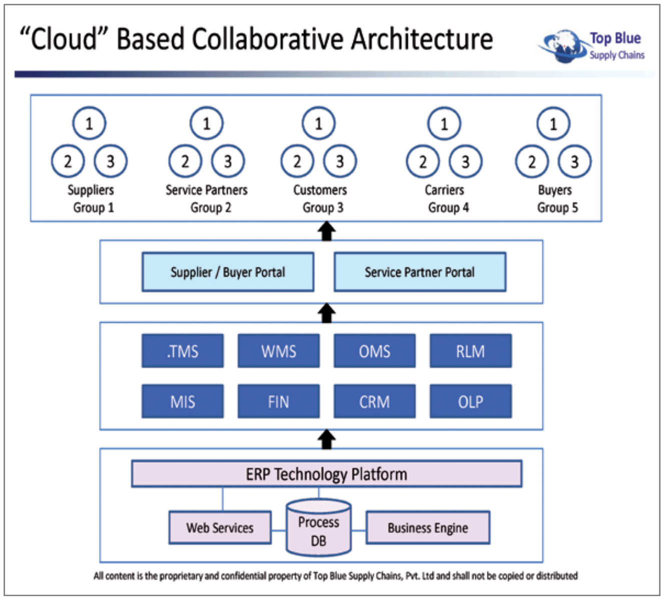

Figure 8: Cloud based collaborative architecture

Conclusion

1. There is a viable market for new cold chain operations, but it has its own realities, rules and practices.
2. By thoroughly quantifying, qualifying and analyzing product needs and issues, a focused market strategy and business case can be crafted.
3. A detailed understanding of the risks, competitive landscape and underlying pitfalls is crucial to entering this market.
4. Profit and ROI are in sight, if the quality delivered translates into attracting adequate throughput of higher than average margin business.
5. Cost controls are essential for efficient and scalable operations. Innovation and optimized hybrid models will help achieve that.
6. Based on the complexities, a comprehensive approach is suggested; one that does not overlook any element that is inherent to the success of the business.
7. Last, but not least, smart performing equipment is not the only key success driver. There needs to be a well-induced culture of quality at every level, and it should cover:
   a. A cold chain participant strategy with multi-party inclusion and benefit, starting with the farmer and ending with the consumer.
   b. A commitment by all to quality performance, from start to finish.
   c. Professional infrastructure project management for on-time, within budget and high quality set up, commissioning and operating discipline.
   d. SCM IT to manage the fastest and most efficient product flow and thus the integrity needed in product value protection.
   e. Skills training oriented towards a self-motivated ambition to understand the 'why' in a task and to do the job right.

Experimental Investigation of Control Strategies

for Off-Design Operation of a Transcritical CO_2 Two-Phase Ejector Refrigeration System for the Cold Chain

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Abstract

The use of two-phase ejectors to improve the performance of CO_2 refrigeration systems has been investigated extensively in recent years. Studies have shown that ejectors offer significant opportunity for COP and capacity improvement at conditions favorable to the ejector; however, performance improvement is known to be less significant at ejector off-design conditions. In this paper, methods for controlling the high-side pressure of a transcritical CO_2 ejector cycle are investigated. The use of a simple expansion valve in series or parallel with the ejector to actively control high-side pressure is investigated experimentally and compared to other studies using an adjustable ejector. Control of the evaporator flow rate for different conditions is also investigated.

Tests are performed at multiple capacities and ambient temperatures in order to investigate the performance improvement offered by an ejector cycle compared to an expansion valve cycle at off-design conditions with and without active control strategies.

Keywords: Two-phase ejector, carbon dioxide, high-side pressure control, capacity modulation

Introduction

Two-phase ejectors are devices capable of improving refrigeration cycle performance by means of expansion work recovery. The most common cycle employing an ejector for work recovery is the standard two-phase ejector cycle shown in *Figure 1*. Much of the recent research on two-phase ejectors has been focused on CO_2 due to the large potential for improvement with this fluid, especially for transcritical operation.

Elbel and Lawrence (2016) reviewed recent two-phase ejector research and noted that the COP of transcritical CO_2 systems can generally be improved by 15 – 30 % by applying a two-phase ejector to the cycle. However, these COP improvements are generally observed at conditions favorable to the ejector cycle

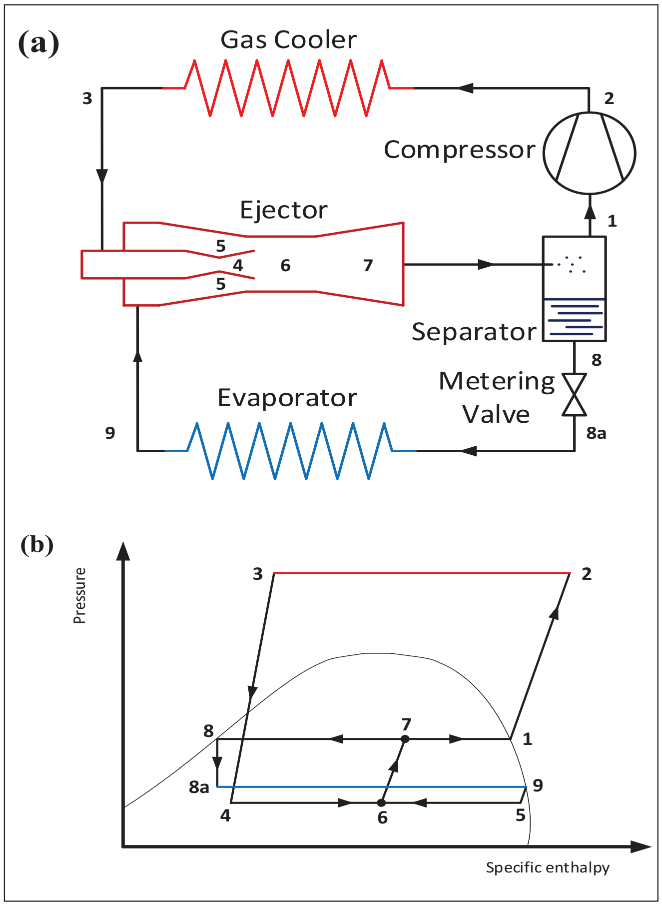

Figure 1: Standard two-phase ejector cycle for transcritical operation represented as (a) schematic diagram and (b) pressure-specific enthalpy diagram

and are not necessarily representative of the improvement that can be achieved at all conditions. In order to achieve reasonable COP improvement with an ejector cycle over a range of conditions, effective control strategies for two-phase ejector cycles must be implemented. Thus, the objective of this paper is to discuss and experimentally investigate the control of a transcritical CO_2 ejector cycle for varying conditions. The effect of using a valve in series or parallel with the ejector to control high-side pressure and the control of the evaporator metering valve are investigated experimentally at multiple capacities and ambient temperatures.

Control of Ejector Cycles

The COP and capacity of a transcritical cycle are very dependent on the high-side pressure of the cycle. An ejector cycle replaces the expansion valve, which can be controlled to optimize high-side pressure in the DX cycle, with a fixed geometry expansion device, for which the high-side pressure is set by the fixed size of the ejector throat. High-side pressure can be optimized in an ejector cycle by varying compressor speed; however, this also results in significant capacity variation as well. This means that some additional control must be added to the cycle in order to adjust high-side pressure and capacity independently. Additionally, the ejector cycle requires a setting for and possibly active control of the evaporator metering valve, as discussed below.

One method of controlling high-side pressure is to use an adjustable ejector in which an adjustable position needle is used to control the effective diameter of the ejector nozzle throat, as shown in *Figure 2(a)*. Elbel and Hrnjak (2008) investigated the use of an adjustable ejector to control and optimize high-side pressure in a transcritical CO_2 cycle. They showed that the overall efficiency of the ejector decreased as high-side pressure was increased. As the needle is inserted further into the throat, the throat size decreases, which increases highside pressure; however, further use of the nozzle also results in greater losses in the nozzle, which decreases the efficiency of the nozzle and the ejector. COP was increased by up to approximately 4 % using the nozzle to optimize high-side pressure (compared to no control of ejector) in the study of Elbel and Hrnjak (2008). A similar study by Xu et al. (2012) observed that COP could be improved by 2 % using this control method.

An additional control option is to use an arrangement of multiple parallel ejectors, as described by Hafner et al. (2014) and shown in *Figure 2(b)*. Each ejector can be turned on and off independently with solenoid valves, allowing for the total effective nozzle size to be varied for different conditions. In comparison to an adjustable ejector, parallel ejectors can control effective nozzle size without the losses caused by the needle; this allows for potentially higher work recovery efficiency with parallel ejectors assuming each ejector operates near its design point. However, Banasiak et al. (2015) observed that the overall expansion work recovery efficiency of a parallel ejector arrangement decreased as motive and suction flow rates increased due to additional frictional losses. Several parallel ejector arrangements have been

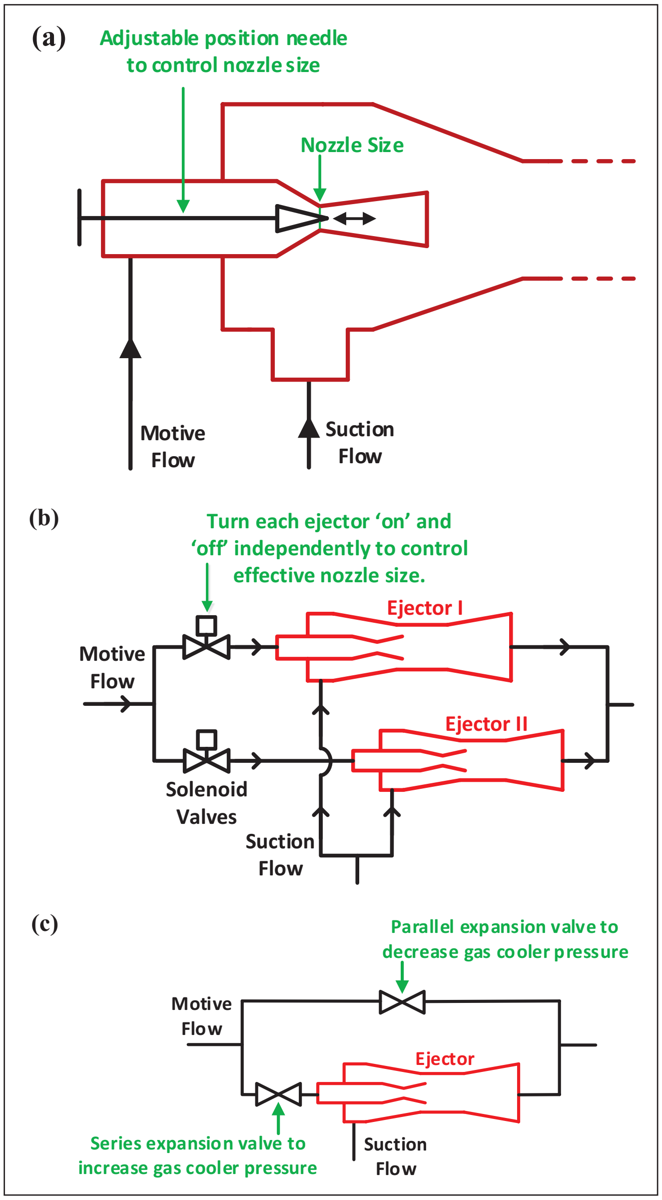

Figure 2: Diagrams of methods to control high-side pressure in an ejector cycle using (a) adjustable ejector, (b) parallel ejector arrangement, and (c) expansion valve in series or parallel with ejector.

installed in CO_2 supermarket systems recently, with improvements of up to 14 % being reported from the field (Schönenberger et al., 2014).

The studies discussed above showed that adjustable and parallel ejectors are effective methods for controlling high-side pressure of a transcritical ejector system. However, these methods are also complex and potentially costly. A simpler option for controlling high-side pressure would be to use an expansion valve in series with the ejector to increase high-side pressure or in parallel with the ejector to decrease high-side pressure, as shown in *Figure 2(c)*. The use of an expansion valve with an ejector would certainly reduce available work recovery but may provide a simple alternative to an adjustable ejector (needle also causes efficiency loss) or parallel ejectors. The expansion valve control method will be investigated further in this paper.

Experimental Facility

The ejector and DX cycles were constructed on an experimental refrigeration cycle test bench. Two closed loop wind tunnels housed the evaporator and gas cooler. Variable speed blowers and electric heaters were used to control the air flow rate and air inlet temperature to the evaporator and gas cooler. A semi-hermetic, reciprocating-type transcritical CO_2 compressor with a maximum speed of 1800 min^{-1} was used; a variable frequency drive was used to control compressor speed. The gas cooler was a four-slab, cross-counter-flow microchannel heat exchanger with an air-side area of 8.80 m^2 and a refrigerant-side area of 0.84 m^2. The evaporator was also a four-slab, cross-counter-flow microchannel heat exchanger with an air-side area of 3.07 m^2 and a refrigerant-side area of 0.39 m^2. An internal heat exchanger (IHX) was also included in the system. Type-T thermocouples, differential and absolute pressure transducers, and Coriolis-type mass flow meters were used to obtain refrigerant-side measurements. Type-T thermocouples, differential pressure transducers, and flow nozzles were used to obtain air-side measurements. A power transducer was used to measure electrical power input to the compressor. Two independent energy balances (air- and refrigerant-side) could be obtained for the evaporator; when both balances were available, they generally agreed to within 2 %. Further description of the experimental facility and the experimental uncertainty can be found in Elbel (2007).

Four different compressor speeds (900, 1200, 1500, and 1800 min^{-1}) were used during the tests in order to show the effect of capacity variation on the performance of the ejector cycle. The evaporator air flow rate and air inlet temperature were 0.25 $m^3\ s^{-1}$ and 27°C, respectively. The gas cooler air flow rate was 0.50 $m^3\ s^{-1}$ for all tests while the gas cooler air inlet temperature varied from 30 to 45°C. The effectiveness of the IHX was approximately 0.6 for all tests. The outlet state of the evaporator was saturated vapor (quality of 1.0) unless otherwise noted for both cycles. CO_2 was used as the refrigerant.

Previous knowledge of ejector design and operation was used to design an ejector for the CO_2 system described here. Two different nozzles were investigated, one with 0.8 mm throat diameter and the other with 1.0 mm throat diameter. Each nozzle had a diverging angle of 2.3° (full angle) and an outlet diameter of 1.1 mm. The mixing section had a diameter and length of 3.0 mm and 24 mm, respectively. The outlet of the nozzle was positioned 11 mm from the start of the constant-area mixing section. The diffuser angle was 5.0° (full angle).

Experimental Results

Evaporator Metering Valve Control

As system capacity varies, a different flow rate through the evaporator will be required, which will require a different metering valve setting if the optimal flow rate is desired at each condition. A flow rate that is too low for the capacity will result in dryout and severely decreased evaporator performance, while a flow rate that is too high for the capacity will result in lower ejector pressure lift. *Figure 3(a)* shows that there is an optimum entrainment ratio (ratio of ejector suction to motive mass flow rates), corresponding to an optimum ejector outlet state that maximizes the COP of the ejector cycle; the optimum evaporator outlet state for this system is an outlet quality of approximately 1.0. *Figure 3(b)* shows that this optimum in COP is due to a trade-off between increasing evaporator UA and decreasing ejector pressure lift as entrainment ratio increases. Compared to the optimum saturated vapor outlet state, lower mass flow results in dryout in the evaporator and lower evaporator UA; while ejector pressure lift is higher for the case of a superheated outlet, the decrease in evaporator UA has a more significant effect on overall cycle performance, resulting in a decrease in COP. Mass flow rate that is too high

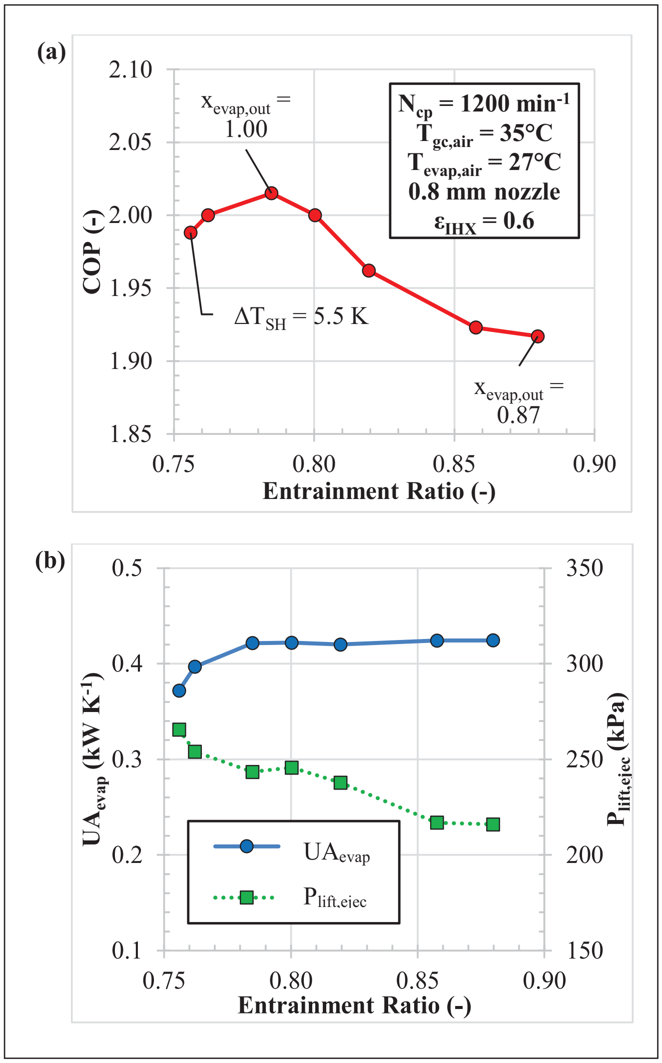

Figure 3: Effect of ejector entrainment ratio (evaporator outlet state) on (a) system COP and (b) evaporator UA and ejector pressure lift.

results in lower ejector pressure lift, as the ejector must pump more mass but with the same power, while evaporator UA does not change significantly once dryout is eliminated; this also results in decreased cycle performance. Note that the optimum outlet state will not be an outlet quality of 1.0 for every system; Lawrence and Elbel (2015) showed that the optimum for CO_2 is generally an outlet quality between 0.9 and 1.0, while the optimum outlet quality for low-pressure fluids would likely be lower.

Figure 4 demonstrates the performance penalty for leaving the evaporator metering valve fixed while capacity varies. Two cases were considered: Valve fixed at 50 % opening (corresponding to the optimum valve setting at 900 min-1) and valve fixed at 86 % opening (corresponding to the optimum at 1800 min^{-1}). The valve was fixed at each of these two settings while the compressor speed was varied. The resulting COP's are shown in *Figure 4* compared to the optimal case (metering valve adjusted to achieve outlet quality of 1.0) at each speed.

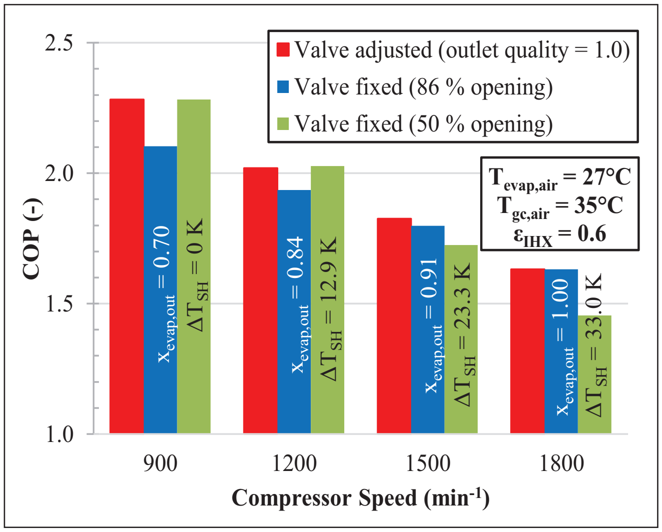

Figure 4: COP obtained by leaving evaporator metering valve fixed at two settings compared to optimal case (metering valve adjusted to achieve outlet quality of 1.0) for different compressor speeds.

Figure 4 shows that for the case of 50 % valve opening, the evaporator superheat increases (up to 33 K) with increasing compressor speed. At higher capacity, the evaporator requires greater flow rate; the smallest valve setting does not allow enough mass flow to the evaporator, resulting in significant dryout and decrease in COP compared to the optimal case. Similarly, for the case of 86 % valve opening, the evaporator outlet quality decreases (down to 0.70) with decreasing compressor speed. At lower capacity, the evaporator requires less flow rate; the largest valve setting allows too much mass flow to the evaporator, which does not necessarily hurt evaporator performance but does decrease the pressure lift of the ejector, ultimately decreasing COP.

Table 1 reports the percent change in COP and capacity for each of the valve settings compared to the optimal case. It can be seen that very significant COP and capacity penalties result from not adjusting the evaporator metering valve. Up to 11 and 17 % penalties in COP and capacity, respectively, are observed if the smallest valve setting is used at higher capacity, while up to 8 % penalty each in COP and capacity are observed if the largest valve setting is used at lower capacity. Gas cooler pressure was not actively controlled for these tests but generally only varied by less than 2 bar for tests at the same compressor speed. It can be seen from the table that the performance penalty for using a valve setting that is too large is less than the penalty for using a valve setting that is too small, meaning that it is better to sacrifice pressure lift with a flow rate that is too large than to allow significant dryout in the evaporator.

Table 1: Change in COP and capacity for two cases of fixed evaporator metering valve compared to optimal case (metering valve adjusted to achieve outlet quality of 1.0) for different compressor speeds.

N_{cp} (min^{-1})	Valve fixed (50% opening)		Valve fixed (86% opening)	
	COP Change	Capacity Change	COP Change	Capacity Change
900	–	–	–8.1 %	–7.9 %
1200	0.0 %	–2.0 %	–4.2 %	–4.1 %
1500	–5.5 %	–9.7 %	–0.1 %	–1.5 %
1800	–10.8 %	–16.9 %	–	–

The results of this section demonstrate the significant effect that control of the evaporator metering valve can have on the cycle. For every system and operating condition, there is an optimum evaporator outlet state and corresponding optimum evaporator metering valve setting. In order to optimize system performance as conditions vary, this valve must be actively controlled. Controlling this valve is not necessarily a requirement for every system, as a system will still function and produce capacity even without control of this valve; however, as demonstrated here, the COP and capacity penalties can be very significant if the valve is not controlled. For a system in which active control of evaporator flow rate is not realistic, the results here suggest that the fixed metering device should be set for a larger capacity and flow rate because an evaporator flow rate that is too high will result in a lower penalty compared to an evaporator flow rate that is too low.

High-side Pressure Control

The performance of transcritical CO_2 cycles is sensitive to high-side pressure, meaning that an ejector cycle must be able to actively control high-side pressure in order to optimize cycle performance over a range of conditions. Several high-side pressure control methods were discussed above, and the use of an expansion valve in series or parallel with the ejector will be investigated experimentally in this section. *Figure 5(a)* shows the COP and capacity of the ejector cycle as high-side pressure is varied at the given conditions. The 1.0 mm nozzle is used in this case. It can be seen that COP improves as high-side pressure is increased (compared to point of no active control), meaning that the 1.0 mm nozzle is likely oversized for this system and condition. It seems that a slight improvement in COP (up to 0.9 %) can be achieved at this condition by increasing high-side

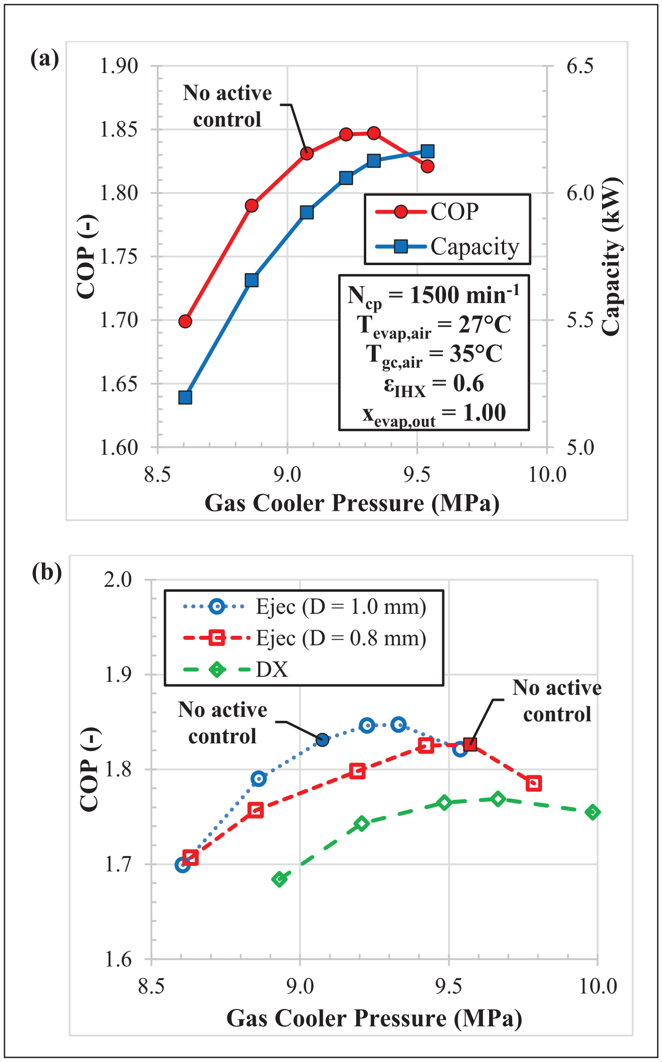

Figure 5: (a) COP and capacity with 1.0 mm nozzle as functions of high-side pressure and (b) COP of ejector cycle (with each nozzle) and DX cycle

pressure by 2.6 bar. *Figure 5(b)* compares the use of the 1.0 mm nozzle to the use of the 0.8 mm nozzle and to the DX cycle. It can be seen that with the 0.8 mm nozzle, almost no improvement can be achieved by using a parallel expansion valve to decrease high-side pressure. However, the COP is essentially unchanged as high-side pressure is decreased by 1.5 bar despite the loss in the expansion valve, meaning that the system must be moving to a more favorable high-side pressure; this also means that the 0.8 mm nozzle seems to be undersized for this system and capacity. *Figure 5(b)* also shows that the DX cycle achieves maximum COP at a high-side pressure near 97 bar, while the ejector cycle optimum high-side pressure is likely lower; simultaneous COP and capacity improvements of 4.4 and 0.9 %, respectively, are observed at this condition.

Figure 6(a) shows the actual work recovered by the ejector, maximum available ejector work recovery (based on the ejector inlet state), and total available work recovery for the entire expansion process (before loss in expansion valve) for different high-side pressures. The difference between the maximum total and maximum ejector work recovery is due to the loss in the expansion valve, and it can be seen from the figure that this loss is significant, even for moderate changes in high-side pressure. *Figure 6(b)* shows the efficiency of ejector and of the whole expansion process. The ejector efficiency is defined as the actual work recovered in the ejector divided by the maximum available ejector work recovery (Elbel and Hrnjak, 2008). The total work recovery efficiency is defined as the actual work recovery divided by the total available work recovery. The difference between the two efficiencies is again the loss in the expansion valve. *Figure 6(b)* shows that the total work recovery efficiency is always less than the ejector efficiency, with the exception of the point where neither valve is used (no active control). The ejector efficiency reaches a maximum of about 25 % at a high-side pressure slightly higher than that achieved with no active control but is seen to

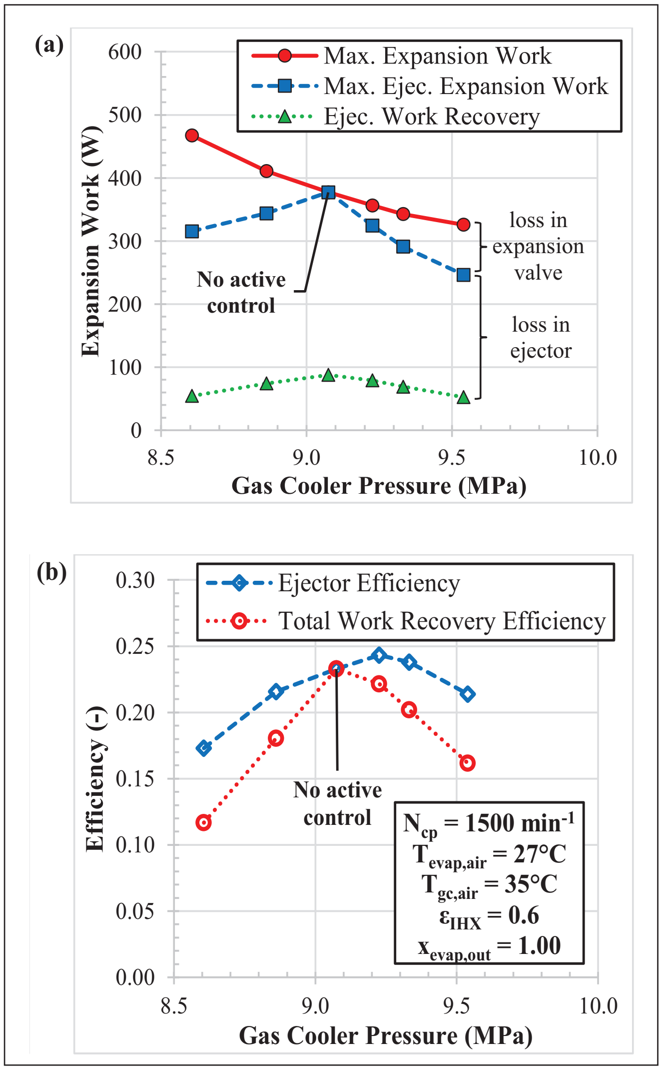

Figure 6: Comparison of (a) maximum total, maximum ejector, and actual ejector work recovery and (b) ejector and total expansion work recovery efficiencies

decrease significantly as high-side pressure varies. The above investigation of COP improvement with the series expansion valve can be repeated at additional conditions. *Table 2* shows the maximum observed COP improvement with the 1.0 mm nozzle and series expansion valve compared to the no active control at four compressor speeds and two ambient temperatures. It can be seen that for each compressor speed, greater COP improvement is observed (up to 3.3 %) at the higher ambient temperature. Similar but slightly less COP improvement values were obtained when repeating the tests with the 0.8 mm nozzle using the parallel expansion valve to vary high-side pressure.

Table 2: Maximum observed COP improvement compared to no active control at each condition.

$T_{gc,air}$	COP improvement with series expansion valve (1.0 mm nozzle)			
	1800 min^{-1}	1500 min^{-1}	1200 min^{-1}	900 min^{-1}
40°C	+1.9 %	+3.1 %	+0.4 %	+3.3 %
35°C	+0.4 %	+0.9 %	+0.1 %	+2.0 %

Figure 7(a) shows that the specific throttling loss (throttling loss per unit mass flow rate) for a given increase in high-side pressure provided by the series expansion valve is the same regardless of ambient temperature. However, a greater ambient temperature also means that there will be more available work to recover. Thus, as shown in *Figure 7(b)*, at higher ambient temperature, the same loss in the expansion valve accounts for a smaller fraction of the total available work recovery compared to lower ambient temperature. At 30°C ambient temperature, increasing high-side pressure by 5 bar reduces available work recovery by about 40 %; this significant reduction combined with the fact that there is less total available work to recover at lower ambient temperature leaves little work that the ejector can actually use. On the other hand, at higher (45°C) ambient temperature, the same 5 bar increase in high-side pressure would only reduce available work recovery by about 25 %; combined with greater total available work recovery at higher ambient temperature, this means that the expansion valve can be used to change high-side pressure by several bar while still allowing the ejector to recover a reasonable amount of work and improve COP. Similar trends are observed for the 0.8 mm nozzle and parallel expansion valve. This may help explain why the expansion valve control strategy is able to provide greater COP increase for both nozzles at higher ambient temperature.

The results of this section suggest that when designing an ejector for a system, it should be designed such that the optimal high-side pressure is achieved at the lowest potential work recovery condition, where active control of high-side pressure is less effective; at conditions of higher potential work recovery, where active control of high-side pressure is more useful, some means of active control can be used to adjust high-side pressure. The expansion valve control method investigated in this paper has been shown to be an

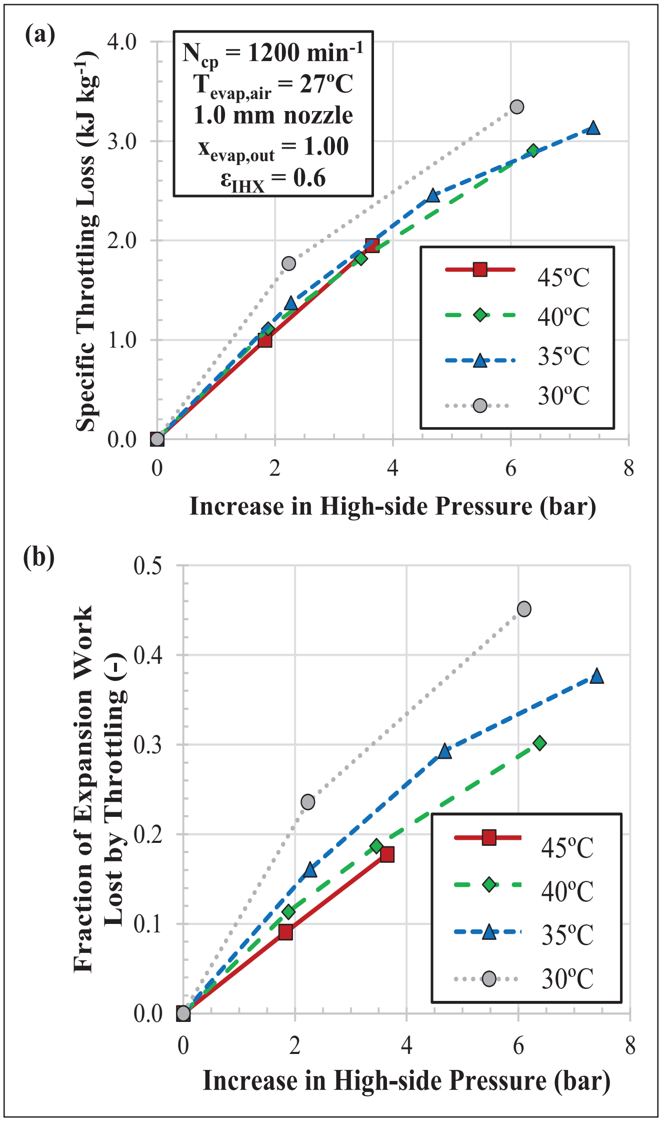

Figure 7: (a) specific throttling loss and (b) fraction of work lost by throttling by using series expansion valve to increase high-side pressure at four different ambient temperatures.

effective method of high-side pressure control, though the COP improvement obtained compared to no active control is somewhat small. However, this is similar to the improvement obtained in studies with an adjustable ejector, suggesting that an expansion valve may offer a simple alternative to the more complex adjustable ejector. The conditions investigated in this paper are not necessarily as extreme as those experienced by a commercial refrigeration system, meaning that greater work recovery would be possible and high-side pressure control would be more effective when applying this or other control strategies to large-scale commercial refrigeration systems. It can also be seen from this study that the penalty for not adjusting the evaporator metering valve was far greater than the penalty for operating at non-optimal high-side pressure. Large-scale systems can control both high- and low-sides simultaneously, though smaller systems may only allow for one means of active control.

Conclusions

This paper has presented the results of an experimental investigation on the control of transcritical CO_2 ejector cycles. Options to control high-side pressure in a transcritical cycle include an adjustable ejector, parallel ejectors, or an expansion valve in series or parallel with the ejector. The experimental results have shown that the use of an expansion valve in series or parallel with the ejector is an effective method to control high-side pressure in the cycle, though the COP improvements obtained by adjusting high-side pressure (up to 3.3 %) were limited due to significant losses in the valve. Active control of high-side pressure seems more effective at higher ambient temperature, where greater losses due to the control device can be tolerated. Control of the evaporator metering valve is also very important for optimizing ejector cycle performance, as the penalty for not actively controlling this valve as capacity varies was seen to be quite significant (up to 11 % in COP and 17 % in capacity).

Acknowlegements

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Nomenclature

Symbols and Abbreviations

COP coefficient of performance (-)
DX direct expansion
IHX internal heat exchanger
N rotational speed (min^{-1})
P pressure (bar)
T temperature (ºC)
UA overall heat transfer coefficient- area product ($kW\ K^{-1}$)
x vapor mass fraction (-)
ΔT_{SH} superheat (K)
e heat exchanger effectiveness (-)

Subscripts

cp compressor
ejec ejector
evap evaporator
gc gas cooler
in inlet of component
out outlet of component

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Arctic Refrigeration Cold Chain Excellence Awards 2018

Tata Strategic Management group presented the Arctic Refrigeration Cold Chain Excellence Awards 2018 on February 23, 2018 at the Leela, Mumbai. The winners were:

- **Best Cold Chain Application Horticulture**
  Fruit Master Agro Fresh
- **Best Cold Chain Application Horticulture**
  Global Entrade
- **Best Cold Chain Application - Dairy**
  Devyani Food Industries
- **Best Cold Chain Application - Meat & Poultry**
  Sneha Farms
- **Best Cold Chain Initiative Food Processing**
  CONCOR
- **Best Cold Chain Application Hospitality**
  Sical Cold Chain Logistics
- **Reefer Container Manufaturer of the Year**
  Reefer India
- **Best Reefer Transport Company Food**
  Rapid Carriers
- **Best Reefer Transport Company-Pharma**
  Mahesh Cargo Movers
- **Best Cold Chain Innitiative - Food Processing**
  ColdStar Logistics
- **Best Cold Chain Transformation of the Year**
  Coldrush Logistics
- **Best Cold Chain Transformation of the Year**
  Mr. Kool
- **Best Project Management Consultant of the Year**
  IL&FS Cluster Development Initiative Limited
- **Best Cold Chain Consultant of the Year**
  Global Agri System
- **Best Nodal Agency for Cold Chain Development**
  National Horticulture Board
- **Best Nodal Agency for Cold Chain Development**
  Assam Horticulture Board
- **Best Nodal Agency for Cold Chain Development**
  Tamil Nadu Banana Growers Federation
- **Largest Temperature Controlled Logistics Project of the Year**
  Snowman Logistics
- **Most Innovative New Cold Chain Technology of the Year**
  Danfoss India
- **Most Innovative New Cold Chain Project of the Year**
  Geetee Carriers
- **New Entrant in Cold Chain**
  D S Group
- **Most Sustainable Temperature-Controlled Project of the Year**
  Crystal Logistic (Cool Chain Ltd)

Association of Ammonia Refrigeration Organises ARCON 2018 at Delhi

The Association of Ammonia Refrigeration (AAR), engaged in promoting safe use of ammonia as a refrigerant for industrial refrigeration applications both in food as well as in process industries, organised its one day annual conference cum mini exhibition ARCON 2018 at Hotel Shangri La, New Delhi on January 19.

Refcon Held in Navi Mumbai

ASHRAE Mumbai Chapter in association with ISHRAE Thane Chapter organised a full day technical programme Refcon aimed at the Food Processing and Cold Chain Industry on January 20 at Country Inn and Suites, Mahape, Navi Mumbai. It was supported by National Centre for Cold-chain Development (NCCD) and Refrigeration and Air Conditioning Trade Association (RATA).

The topics covered included Effective Cold Supply Chain Management, Refrigeration Plant Productivity, Automation and Energy Management for Cold Storage, Intelligent Food Logistics and Property Loss Prevention in Food Processing Facilities.


Harshal Surange and K. Ramachandran light the lamp

Harshal Surange addresses the audience

Bharat Jare, President – ISHRAE Thane Chapter, welcomes the delegates


Madhavi Ramachandran speaks on Cold Chain Management in Food Industry

Carrier Transicold India

Pankaj Mehta
Managing Director

Carrier Transicold India has been an industry leader for more than two decades and is providing customers advanced, energy-efficient and environmentally sustainable direct-drive units, diesel-truck units and trailer refrigeration systems for temperature controlled transportation of fresh and frozen food, dairy, pharmaceuticals and other perishables. A skilled team of certified technicians, regularly trained in the installation, maintenance and repair of Carrier Transicold refrigeration systems, is available to support customer fleets through a pan-India network of service centres.

Over the last 3 to 5 years, the organized retail and food services industries have emerged as new segments for the cold chain in India. There is a clear and gradual shift in consumption patterns in favour of ready-to-eat food and the emergence of leading quick service restaurant chains. Organised retail of frozen meats and fresh vegetables in malls and other retail stores has also increased.

But there are many more potential customers who are not participating in the cold chain because they perceive it as either too costly or too complex. To tap this customer segment, Carrier Transicold has recently introduced the Citifresh™ range of direct drive truck units, which is an affordable solution for transporting chilled products on medium- to large-commercial vehicles.

The Citifresh range has a robust design and stainless steel evaporator that is easy to install and maintain, and is suitable for demanding applications including high ambient conditions up to 50°C. The range has a low initial cost and lower maintenance and operational costs.

Carrier Transicold saw a challenge with low engine speed on last mile delivery vans moving across congested city roads, which led to direct drive compressors not achieving consistent cooling capacity. To meet this requirement, Carrier introduced the Pulsor™ refrigeration unit for light commercial vehicles, featuring E-Drive™ all-electric technology, which eliminates the road compressor and replaces it with a small electric generator that powers a hermetic compressor to deliver constant RPM.

In line with the growing requirement of real time monitoring and tracking systems, Carrier Transicold has introduced advance telematics solutions for diesel drive truck and trailer units. These systems enable customers to remotely monitor and control their refrigeration units and help them track their consignments with a strict watch over temperature integrity. This has helped them track and reduce theft, secure and control the number of door openings and optimize time for loading and unloading. Smart features such as alerts and alarms, geo-fencing and geo-tracking have helped customers improve their delivery timelines.

Carrier Transicold works with stakeholders – including large logistics companies, leading truck manufacturers, insulated box manufacturers and end users – to offer customised solutions, integrate reefer equipment with the vehicle and to install and commission the equipment. Its products cover a wide range of transport customer requirements and integrated cold chain management from a small distribution van to large 12-meter trailers, and are designed to operate in ambient temperatures ranging from -30°C to +50°C in both single temperature and multi-temperature versions.

The Oasis™ and Supra® range of large trucks comes with its own engine and can run independently of the truck engine. The Oasis range is designed to provide reliable performance in hot, dusty ambient conditions and offers faster pull-down and higher cooling efficiency in ambient temperatures of the order of 50°C.

For more information, visit *www.transicold.carrier.com*


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