



INDUSTRIA formazione

special international issue
refrigeration and air conditioning



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climate change
energy efficiency

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UNDER THE AUSPICES OF THE ITALIAN MINISTRY OF THE ENVIRONMENT

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15033 Casale Monferrato
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Advertisement:

Phone +39 0142 453684

Publisher:

A.Vi. Casale Monferrato

Published by:

A. Valterza - Casale Monferrato

www.centrogalileo.it

website of the activity

www.associazioneATF.org

website of the Italian Association
of Refrigeration Technicians



On the
left
picture
of the
cover
ISI 2006

**About the picture on the cover:
as ISI 2006 this image of Achill
Island, off the most North-Westerly
point of Ireland, illustrates:**

- Ozone protection

the sky: the blue sky contains our
Earth's ozone shield.

- Climate change

the sea: higher temperatures
could lead to sea level rise and
extreme weather events.

- Energy efficiency

the waves: renewable energy
sources such as waves are
waiting to be harnessed.



Supplemento 1 al N° 321 (N° 7-2008) -
Periodico mensile - Autorizzazione del
Tribunale di Casale M. n. 123 del
13.6.1977 - Spedizione in a. p. - 70% -
Filiale di Alessandria - ITALY.

This magazine has been produced with
paper E.C.F. (Elementary chlorine Free)

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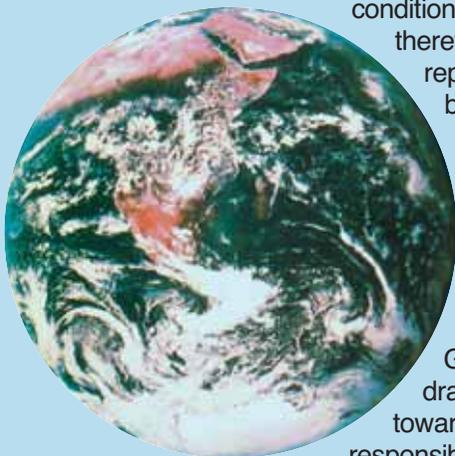
FOREWORDS

In today's economically volatile climate, any environmental solutions that provide economic advantage are welcome. Such is the case with climate change and ozone depletion - two of today's most pressing global environmental challenges. While they present distinct threats, they also have key interlinkages, which offer significant economic opportunities when both problems are addressed simultaneously. Recent scientific and technical assessments have indicated that since 1990, actions under the Montreal Protocol in phasing out ozone-depleting substances will have had the additional benefit of delaying climate change by up to 12 years by reducing greenhouse gas emissions by about 11 billion tonnes CO₂-equivalent per year. This dual success is set to continue. The historic agreement reached in 2007 by the Parties to the Montreal Protocol to accelerate the phase-out of HCFCs - chemicals that were used to replace the more ozone-damaging CFCs - will not only assist in the restoration of the ozone layer but could play an important role in addressing climate change. The HCFC phase-out presents us with an unparalleled opportunity. With the adoption of the best alternatives, we can contribute to eliminating ozone-depleting substances and at the same time assist climate change mitigation, improve energy efficiency and contribute to wider environmental, social and economic benefits. G8 countries recently explicitly expressed the objective to ensure that actions under the Montreal Protocol to phase out ozone-depleting substances also support energy efficiency and climate change objectives. Depending on the replacement technologies adopted, the HCFC phase-out could deliver cumulative emission reductions over coming decades of between 18 and 25 billion metric tonnes of CO₂-equivalent. In addition, the replacement technologies will provide an opportunity for significant economic benefits through improved energy efficiency. Refrigeration and air-conditioning represent the major use of HCFCs. Consideration of replacements in this sector is therefore particularly important. An impartial evaluation of the relative merits of HCFC replacement technologies and chemicals for refrigeration and air conditioning, including both fluorinated and natural refrigerants, is essential. I hope this magazine will provide a useful contribution to this effort.

Achim Steiner

United Nations Under-Secretary-General

Executive Director of the United Nations Environment Programme



Global climate change and the effects on our future are topics of dramatic importance which require urgent answers. Italy will work towards international agreements which make everybody seriously responsible for the Kyoto Protocol. Our country will hold in 2009 the Presidency of G8: we will use the occasion to achieve concrete commitments, undersigned by those who are small polluters but above all by big polluters. Twenty years after the signing of the Montreal Protocol, the fight against the reduction of the ozone layer is still a priority for the European Union. Italy is proud to have played an effective role in the implementation of the Protocol and is strongly committed in this aspect encouraging technological innovation. The Environmental Ministry will continue doing that. Since the overheating of the planet is the real world emergency, at a national level we must save energy, promote renewables, use less polluting fuels. Intervening in the building envelope and in clean energy production is also the first step for a new constructive mentality with a view to a more respectful and aware living not only for the area where we live but for the entire globe. The debate on the energy saving in the sector of construction is concentrated on one hand on the structural components, studying adequate solutions to contain the dispersions, and on the other hand on emission reduction of pollutants, aiming the optimization of plant efficiency. Increasing requirements for comfort and with summers even more torrid will involve, especially in Italy, a larger demand for air conditioning. So it is vital, in this context, to invest in the correct ventilation management and the latest technologies in refrigeration and air conditioning are a relevant help in that direction, in the field of environmental safeguard. Centro Studi Galileo is doing the right thing promoting different initiatives to increase the awareness of this problems, looking to contribute for a better future.

Stefania Prestigiacomo

Italian Minister of the Environment



Editorial

Working together with the major experts towards “the future of refrigeration”: XIII European Conference

MARCO BUONI
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italiani del Freddo - ATF*

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INTRODUCTION

The second edition of the International Special Issue 2008 takes its cue from the first edition which was a great success. It was delivered at New Delhi's UN Summit of Montreal Protocol to Head of States and Ministers (2006) in order to show the environmental problems linked to refrigeration and air conditioning.

The previous issue has been also delivered to various other UN summits including Nairobi's 2006 and Bali's 2007 Conferences of Kyoto Protocol and the XII European Conference of Centro Studi Galileo.

As in 2006 and 2007, the new ISI 2008 will be distributed also to the worldwide operators of refrigeration and air conditioning connected with the United Nations and the International Institute of Refrigeration and the 13th European Conference of Centro Studi Galileo and of Associazione dei Tecnici del Freddo in which all the major associations and World Organizations will also participate.

LATEST REFRIGERATION AND AIR CONDITIONING TECHNOLOGIES IN RELATION TO THE ENVIRONMENT

The International Special Issue first edition 2006 was born with the purpose of showing in a popular way the environmental problems connected with refrigeration and air conditioning.

Refrigeration and Air conditioning are nowadays fundamental elements in the everyday life of human beings -



Didier Coulomb, Marco Buoni, Rajendra Shende in the IIR offices in Paris.

technologies which we cannot do without. They have also been very important for the economic expansion that we have seen in the last century: the International Institute of Refrigeration (IIR) as well as various national associations of refrigeration (AFF,...) have launched in 2008 the “Refrigeration Year”. They will be celebrating their centenaries.

Refrigeration has permitted the transportation and preservation of food in every part of the world avoiding food waste. Air conditioning has permitted comfortable conditions of living and working both in seasons and countries particularly warm and humid.

Refrigeration has been the key driver of Montreal Protocol related achievements in the addressing of ozone depletion. By phasing out CFCs, the impact of the Montreal Protocol has been 5 times as effective as that of the Kyoto Protocol in terms of mitigation of global warming: refrigeration is already within a sustainable development framework.

These technologies, essential for humanity, are however still important factors which have to be controlled for the safeguarding of the environment. ISI 2006 had explained the problems connected with refrigerants CFC, HCFC - responsible both for Ozone Layer Depletion and Climate Change. Present HFCs, which often replace CFCs and HCFCs, have a high global warming potential. We must search other solutions.

This second edition has evolved naturally and it is realized by UNEP, IIR and CSG underlining which are the alternative technologies to avoid environmental problems in the future.

ISI 2008 is centred on the latest exploitable and available technologies to replace HCFCs in the area of Ozone protection and Climate Change prevention in refrigeration and air conditioning taking into account energy problems, the environment, climate change and energy efficiency. It is focused on solutions like natural refrigerants, absorption systems, solar cooling, magnetic refrigeration with practical case and specific examples.

In this magazine the major associations, institutes and worldwide organizations describe the above subjects in a complete manner, explaining the advantages of the technologies and how those, in the different regions of the world,



Rajendra Shende and Didier Coulomb were Presidents in the last XII European Conference on Technological Innovations in Air Conditioning and Refrigeration. The next conference will be held in Milan the 12th-13th June 2009.

Among the international Associations that collaborate in the conference XIII European Conference UNEP-IIR-CSG there are:

- ATF (Association of Italian Technicians of Refrigeration)
- AREA (Air Conditioning and Refrigeration European Association),
- AFF (French Association of Refrigeration),
- ASHRAE (American Society Heating Refrigeration Air conditioning Engineers)
- AICVF (the French Association of Engineers of the Air conditioning, Ventilation and Refrigeration), and many more which write on this issue.

These associations / institutes are among the most important in the refrigeration and air conditioning field and most of them have contributed to this special international issue.

The International Institute of Refrigeration also organizes numerous international conferences on various subjects dealing with new technological developments in the refrigeration fields: see www.iifir.org

IMPORTANCE OF TRAINING

The role of Centro Studi Galileo, the International Institute of Refrigeration and the United Nations Environment Programme (www.unep.fr/ozonaction) is not only to organize scientific and technical conferences. It is also necessary to write courses and to organize trainings for technicians and engineers who will build new plants with a better environmental impact and who have to properly maintain plants, without refrigerant leakages.

The IIR publishes several courses: see www.iifir.org and organizes courses in various countries on a case by case basis. Centro Studi Galileo organizes about 200 technical seminars and trainings for technicians all over Italy. These take place in different training sites and in the main Italian Universities, teaching every year more than 2.000 attendants the procedure to have a perfect maintenance, installation and design, in order to optimize their work and consequentially to reduce energy efficiency and environmental dangers.

We would thank all the authors of the articles for the time they have dedicated to write this brochure. They are members of various organizations, universities and private companies, which work in the refrigeration fields in order to mitigate the impacts on environment: it is a collective work.

We also would thank the Italian Minister of Environment Stefania Prestigiacomo for her support, which has allowed us to publish this document. Italy thus contributes to a better global environment.

could be helpful to improve the environment and to solve the problems connected to it.

Each application of refrigeration needs adapted solutions. It was impossible to cite all of them, either because the application is very specific, either because solutions are very soon emerging, as it is the case in mobile air conditioning: the latest European regulation impose a refrigerant with a Global Warming Potential below 150. Two technologies are now competing: CO₂ as a refrigerant and new synthetic refrigerants.

XIII EUROPEAN CONFERENCE UNEP-IIR-CSG

In the matter of the latest technologies in refrigeration and air conditioning Centro Studi Galileo, editor of ISI 2008, organizes every 2 years a European conference.

The next XIII UNEP-IIR-CSG European Conference, will be held in the Politecnico of Milano and it will see the participation, besides the authors of the ISI 2008, of all the major international experts in HVACR sector.



Technical training about solar energy in refrigeration and air conditioning held in Politecnico di Torino, in the picture Rajendra Shende gives the participation certificate to the attendants.

Special interview



“Convenient Opportunity to Address an Inconvenient Truth”

RAJENDRA SHENDE

Head, OzonAction, UNEP DTIE, Paris

Rajendra Shende, Head of OzonAction, of United Nations Environment Programme (UNEP) and one who for more than a decade, promoted ‘One solution for Two Protocols’ talks here with Marco Buoni, Head of the editorial team. The two Protocols referenced are the Montreal Protocol and the Kyoto Protocol. Early on, many of the substitutes of Ozone Depleting Substances were also Greenhouse Gases, more dangerous than carbon dioxide. For example, HFCs substituted CFCs and they were an acceptable solution under the Montreal Protocol. But emissions of HFCs were controlled under the Kyoto Treaty. The international regime of environmental negotiations has taken time to resolve this dilemma. In September 2007, 191 Parties to the Montreal Protocol took another momentous decision to advance phase out of HCFCs which presents an unparalleled opportunity to contribute to prevention of Climate Change. The global environmental governance scenario is changing fast: Interview follows.

Why is the accelerated HCFC phase out in 2007 so important for the world community?

HCFCs are mild Ozone Depleting Substances as compared to CFCs. Their ODS potential is only about 5 % of that of CFCs. Hence, the phase out dates was agreed 2040 - a very long period indeed! Literally 5 generations

can watch the slow phase out of HCFCs. Obviously, the message the industry and the consumers got was: there is no urgency to act in getting rid of HCFCs. In fact, in a number of cases, HCFCs are used as substitutes for CFCs. The result of such ‘glacier’ speed of the HCFC the phase out was the ‘jet’ speed in the rise of its production and consumption. Between 1989 and 1996 the consumption doubled. It doubled again from 1996 to 1999. And it doubled once again from 1999 to 2004. The best guess is it must have doubled once more from 2004 to 2008. It is estimated that in year 2010 it could cross 800,000 tones per year.

Imagine that when shares of a company are rising steeply, the management of the company decides to stop manufacturing. This is what happened in the case of HCFCs in the year 2007, when the Parties to the Montreal Protocol took the decision to accelerate the phase out.

Why you think that such a decision was taken in 2007? Why was it not done earlier?

It was a question of priority. The Montreal Protocol is really the first international environmental treaty with a time-bound obligation accepted by 193 Governments in the world. Hence, Parties considered that in eliminating 97 Ozone Depleting Substances (14 of which are the majors in terms of volumes consuming ODP of the substances) there is a need to get rid of those ODS first which have a higher ODP. HCFCs have a much lower ODP

ranging from 0.1 to 0.02 as compared to CFCs and Halons which have an ODP ranging from 1 to 10. Therefore the phase out schedule of HCFCs first agreed in 1992 in Copenhagen was much slower and longer term, i.e. by 2040. This was really a long period, almost equivalent to a generation gap! However, as the world progressed in implementing the Montreal Protocol, the success of the phase out of CFCs prompted two considerations, first: it was evident to policy makers that getting HCFCs phased out earlier than 2040 is important as their consumption was going steeply, second: there were clear climate benefits to avail. These were low hanging fruits to take benefit from. The scientific paper by Mr G. Velders (The importance of the Montreal Protocol in protecting climate, 20 March 2007) very clearly demonstrated the climate benefits that already accrued by global phase out of more than 95 % of ODS. This paper, as well as IPCC/ TEAP report, i.e. Special Report on Safeguarding Ozone Layer and Climate System, analytically put forward the future climate benefits till 2015 and beyond by phasing out. The governments reacted to these scientific and technical findings.

All this explains that time was ripe to take a decision of accelerated phase out of HCFCs.

If ODP of HCFCs is only 5 % of CFCs, is the world really going to benefit by its accelerated phase out of HCFCs? How?

It is evident therefore that HCFCs

phase out helps ozone layer protection as well as climate change, but more than that it helps the economy. It also contributes to energy security. These far wider environmental, social and economic benefits arising out of HCFC phase out have not been fully recognized. Accelerated phase out of HCFCs offers the world “quick wins” in addition to mitigating climate change and builds confidence that a new international regime on GHG emissions can be agreed before the first phase of Kyoto Protocol expires in 2012.

Climate benefits of accelerated phase out of HCFCs comes from:

- Reduction of emission of HCFCs from the equipment (e.g. refrigeration equipment) and from foams which are blown with HCFCs by using best practices
- Reduction in production and consumption of HCFCs by adopting lower GWP alternatives to HCFCs
- Improving in energy efficiency of the equipment using alternatives to HCFCs.
- Destroying HCFCs at the end of life.

Frankly, the decision of Parties to the Montreal Protocol to accelerate phase out of HCFCs is going to benefit climate change regime more. The ODP of HCFCs is 20 times lower than CFCs, but the GWP of HCFC is 2000 tons more than that of

CO₂. Phase out of HCFCs would advance the recovery of ozone layer by about 10 years, whereas it would delay climate change by many more years. Accelerated phase out of HCFCs could reduce emissions by about 18 GT CO₂-eq. between 2010 and 2050. This is significant if we compare that the reduction expected from Kyoto Protocol between 2008 - 2012 is 5 GT CO₂-eq. If zero or low GWP substitute technologies are adopted by countries to replace HCFC usage this cumulative emission reduction is certainly feasible. There is also an opportunity to gain additional climate benefits through improved energy efficiency in appliances including room air conditioners using HCFCs. Such measures would take the cumulative climate advantage to equivalent of about 38 GT CO₂-eq. For example, based on the IEA's calcu-

lations related to energy efficiency of room air conditioners in China's warm provinces, if energy efficiency levels are achieved as much as those achieved for Japanese room air conditioners, the reduction in total power requirement could be between 15 - 30%. If calculated over the next 15 years, this could amount to 260 TWh which is equivalent to output from 50 average power plants of 5 TWh capacity each.

What are the steps that UNEP's OzonAction is proposing to enable developing countries to take on climate benefits from accelerated phase out of HCFCs?

The UNEP OzonAction strategy to enable 145 developing countries to



The International Special Issue 2006 has been launched in a Press Conference in the Protocol Montreal Summit in New Delhi by Rajendra Shende and Giovanna Piccarreta of the Italian Ministry of Foreign Affairs.

avail this extraordinary opportunity. There is now global, regional and national infrastructure that has been strengthened and capacity built in the developing countries as a result of phase out of HCFCs to take this issue head on.

It is true that in terms of sheer volume, the amount of HCFCs that developing countries have to phase out by 2030 is far larger than the CFCs that they will have phased-out by 2010. However they now have ‘hands-on’ experience in phasing out more than 90% of the CFCs and some other ODSs, and more than that they know that while implementing the Montreal Protocol, this is contributing to environmental and development goals.

UNEP OzonAction has an overall mandate to enable countries to meet compliance with the Montreal Protocol

through capacity building and technology support. While implementing this mandate, UNEP will utilise the lessons learned over the last 20 years in working with the developing countries through delivery of its integrated services, such as information exchange on technologies and policies, regional networking of the National Ozone Units, training of the technicians, policy makers and customs and monitoring officers.

The foundation of this exercise will be laid by developing the HCFC Phase-out Management Plan - HPMP-through a participatory approach. UNEP OzonAction has gained experience from developing the Country Programmes in more than 100 countries. Based on the lessons-learned, UNEP has developed a guidance manual for the development of HPMPs which will play a key role in developing the HPMPs in nearly 60 countries, including India and China.

Through its regional networking and thematic workshops, UNEP will disseminate the technology information and that while contributing to solving these two global problems, countries have unparalleled opportunity to get notational benefits by reducing energy consumption.

Communicating the multiple advantages at the global and local level will be the key element of UNEP strategy. UNEP's web-based HCFC Help Center will become a hub for the information on alternative technologies and policies particularly adapted to low or zero GWP and of improved energy efficiency.

What I would like to state on behalf of UNEP OzonAction is:

The second phase of the Montreal Protocol has dawned upon us. The morning of the second phase comes with a golden opportunity to simultaneously protect the ozone layer, curve the GHG emissions and reap economical and developmental benefits for long-term sustainability.

This second phase of the Montreal Protocol provides very strong confidence-building ambience for the negotiations leading towards the second phase of the Kyoto Protocol.





Refrigeration for sustainable development. History and challenges

DIDIER COULOMB

Director International Institute of Refrigeration - IIR



The International Institute of Refrigeration (IIR) is an independent intergovernmental science-based organization which promotes knowledge of refrigeration and associated technologies that improve quality of life in a cost-effective and environmentally sustainable manner including:

- Food quality and safety from farm to consumer
- Comfort in homes and commercial buildings
- Health products and services
- Cryology
- Energy efficiency
- Use of non-ozone depleting and low global warming refrigerants in a safe manner.

Web site: www.iifir.org

INTRODUCTION

Refrigeration, including air conditioning, is now at the heart of global environmental challenges, because of its impacts on the ozone layer and on global warming.

Recent and probably future measures will need many changes in this sector. However, refrigeration is necessary for life and the aim is to ensure that this sector will continue to expand, but in a sustainable way. A historical perspective is necessary to understand the former evolution of the needs of refrigeration and of the various technologies that have been used, in order to anticipate future evolutions.

A 100-YEAR HISTORY

Man has always needed cold (1): preservation and transport of foodstuffs thanks to snow or natural ice have been reported in the Roman Empire; ice was used as a means of transport (marble in the Forbidden City in China) or as a construction material for houses (igloos in Greenland)... Because temperature is a magnitude and a key variable in physics, chemistry and biology, and characterizes the state of matter and liquid, solid and gaseous phases, which is vital to all living beings: each living being (bacteria, plant, animal) has a temperature range within which it can live; each pathogen can grow, survive or not according to the temperature.

Foodstuffs are thus chilled or frozen to ensure that they are healthy and to prevent the growth of pathogens.

The 19th century was the key century. This was a great century for scientific and technical discoveries, particularly in the field of thermodynamics. The Industrial Revolution took place in the 19th century and required refrigeration: dairy products, meat, breweries.... And of course ice making. The advent of railways and steamships boosted trade in natural ice from Scandinavia and Canada, but suppliers could not keep pace with the growing demand. Furthermore, rising concern about the sawing of blocks of ice from polluted rivers and lakes gave extra impetus to the development of machines that could manufacture clean artificial ice. These machines

have been developed since the middle of the 19th century. There were two developmental axes: supply and transport of foodstuffs (first boat to transport meat between South America and Europe in 1876, Le frigorifique); mastering matter through gas liquefaction (hydrogen, helium,...) with applications developed during the 20th century (health, space, energy supply and transport...).

In 1908, the First International Congress of Refrigeration took place in Paris, France, with about 5000 participants of 40 countries. Representatives from the worlds of science, commerce, industry and government exchanged views on low temperatures, refrigeration technology, food, applications of artificial cold in trade and industry, and legislative issues. The Congress culminated in the founding of the International Association of Refrigeration, which became the International Institute of Refrigeration (IIR), an intergovernmental organization, in 1920.

Throughout the 20th century, this interaction between science and industry led to the providing of goods and the setting up of services vital to mankind:

- cryogenics: air separation for medical uses (cryosurgery, anaesthesia); petrochemical refining, steel production.. ; space propulsion fuels, superconductivity for large research instruments, energy (thermonuclear fusion...), medical applications (scanners..), transport and distribution of natural gas or hydrogen, manufacturing of semi-conduc-

tors, sequestration of CO₂, conservation of species...

- other health uses: preservation of cells, tissues, organs, embryos... surgery and operating theatres, manufacturing and transport of drugs, vaccines...

- air conditioning: vehicles, living areas, integrated systems (heating and cooling) with heat pumps, offices and factories, particularly in hot climates but also for technologies (electronic components, computer technology, biotechnology)...

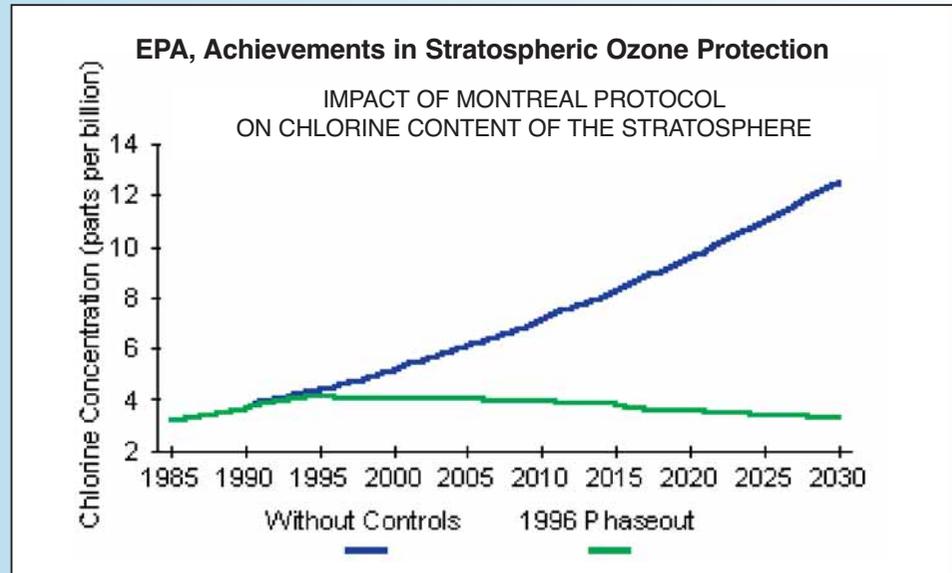
- food: manufacturing (texturation, formulation, freeze-drying, fermentation, concentration and separation), storage, transport, commercialization.

- public works, leisure activities...

Despite various other technologies tested in the 19th century, most of the technologies used in the 20th century and today are vapour-compression systems, which use refrigerants. Many refrigerants were also tested. No single refrigerant was perfect (flammability, toxicity, efficiency...). No single refrigerant could be used in all conditions, for all uses with all kinds of materials (corrosion...). Two types of refrigerants dominated the 20th century: ammonia, for large industrial systems (food processing and storage) because of its efficiency; chlorofluorocarbons (CFCs) and little later hydro chlorofluorocarbons because of safety and durability, for other applications. Because of the environmental impacts of these refrigerants, discovered in the 1970s, changes had to be implemented (cf III).



IIR offices: on the left Didier Coulomb showing ISI 2006, on the right Marco Buoni-ATF.



REFRIGERATION IS NECESSARY FOR MANKIND

Uses of refrigeration are numerous. However, health issues are, with environmental issues, the main challenges for the 21st century. Because of the role of refrigeration in the preservation of health, it is necessary to emphasize key figures.

Uses of refrigeration for hospitals or health products have already been presented (I). But the main use of refrigeration is still the preservation of foodstuffs.

As crystallized by Robert Heap(2)

“Food safety and food security are very important. Deficiencies in these may result in illness or death, in many people being undernourished, in valuable foodstuffs being lost, and in problems of proper disposal of unfit food. There is increasing interest in energy use and carbon footprints; food wasted through poor food safety measures results in waste of the energy used in food production, transport, and storage.”

According to the FAO, more than 800 million people worldwide are undernourished, mostly in Asia and Africa.

“Until now, most measures to overcome under nourishment have concentrated on increasing agricultural output. But it is also important to reduce losses, and here refrigeration can help. Out of a worldwide agricultural output of 5500 million tonnes (including fish and seafood), only an estimated 400 million tonnes are

refrigerated (i.e. chilled or frozen). The IIR(3) estimates that 1800 million tonnes would benefit from refrigerated storage or transport. The development of better-refrigerated cold chains can therefore be an important aid to security of food supplies. Freezing food enables it to be kept safely for long periods. Foodstuffs last longer for being chilled, but still have a limited life”. Loss of unsold chilled foods also waste food.

“What are the hazards to food safety, and to what extent can refrigeration help to overcome them? Food safety hazards may be categorized as physical, chemical and biological. Physical hazards include foreign bodies (glass splinters, sharp bones) and also unwanted additions such as caterpillars - refrigeration cannot minimize such hazards. Chemical hazards include contaminants, residues and additives. Most consumers are concerned about pesticide residues and food additives; most scientists place greater importance on natural toxicants, followed by pesticide and drug residues. Again, refrigeration cannot help, but it is important to realise that chemical hazards actually are less frequent causes of food-borne illness than biological hazards, which can be controlled by refrigeration.

The biological hazards of bacterial infection and of bacterial toxins can be minimized by proper use of refrigeration, combined with proper hygiene procedures. More than 200 known diseases may be transmitted through food, which may appear unspoiled

even when containing excessive numbers of disease-producing organisms. A study in the USA (1999) showed the number of illnesses and deaths from food borne pathogens. Annually, there were an estimated 1777 deaths and 13.65 million illnesses from known pathogens, out of a total of 76 million illnesses and 5000 deaths from all food borne diseases.

The actual causes of food poisoning are contamination, microbial survival, and microbial growth. It is clear that improper refrigeration is the largest factor: over 90% of these illnesses are at least partly associated with temperature control.

That issue will certainly be taken into consideration to a greater extent in the coming years. The population is increasing (more than 9 billion inhabitants in 2050, 1/3rd more than now), essentially in developing countries where the cold chain is underdeveloped. Moreover, the population living in cities will double in these countries. In developed countries, the dominantly urban population will comprise rising numbers of elderly persons who are more prone to foodborne illnesses than younger persons. Air conditioning will also be more necessary for these elderly persons.

THE ENVIRONMENTAL ISSUE (4)

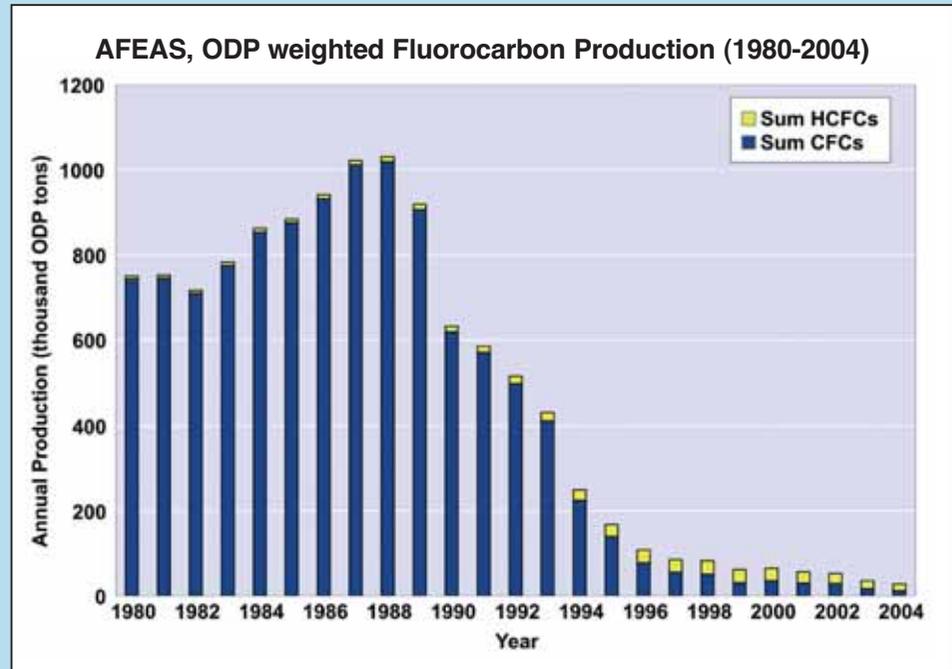
Until the 1970s, only toxicity and flammability of certain refrigerants were environmental problems.

“The ozone layer

In 1974, Molina and Rowland noticed depletion of the stratospheric ozone layer protecting the Earth from harmful ultraviolet solar radiation for the first time.

Soon, several chemicals were incriminated, even though the debate concerning the ongoing chemical and physical phenomena and who was responsible lasted a decade.

Chlorinated substances such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) used in aerosols, foams and as refrigerants were among these substances. CFCs, R12 in particular, and HCFCs soon after, had widely replaced previous refrigerants, with the exception of ammonia.



The 1985 Vienna Convention marks a relative scientific and political consensus in favour of the progressive phase-out of ozone-depleting substances and led to the signing of the Montreal Protocol in 1987. This Protocol was then progressively signed (over the next 15 years) by various stakeholders and was rapidly implemented thanks to the immediate involvement of the main contributors: governments of developed and developing countries, but also industrial stakeholders, manufacturers and users of these substances. The progressive phase-out time frame of these substances until 2040, demonstrates a willingness to apply long-term planning.

The Protocol made it possible to develop new refrigerants without any impact on the ozone layer (hydrofluorocarbons, HFCs) or to rediscover old no longer used refrigerants, such as carbon dioxide (CO₂), that could be made competitive thanks to a few technical improvements.

This Protocol was a widely acclaimed worldwide success, probably because it was unfortunately one of the only true achievements of international cooperation. Current measurements of the ozone layer show an overall stability and probable recovery to the previous level around 2060.

Global warming

Meanwhile, scientists gradually alerted

the public about another phenomenon: global warming. Rising global temperature measurements and their correlation with the increase in CO₂ in the atmosphere progressively led observers to notice that human activity produced gases that significantly increased the natural greenhouse effect around the Earth. This theory raised controversy initially, but is now very broadly accepted by the scientific community. It led to the signing, by the international community, of the Rio Convention in 1992, then the Kyoto Protocol in 1997.

Several greenhouse gases were identified. The main one in terms of its global impact, due to the quantities released (as its global warming potential is very low) is CO₂. CO₂ emissions are essentially due to the burning of fuel in transport and the heating of buildings, to industrial processes using fossil fuels and to power production. Electricity is mainly produced from oil, coal or natural gas in most countries. Other greenhouse gases exist, in particular refrigerants: various CFCs, HCFCs, and HFCs have a global warming potential that is about 100-10 000-fold that of CO₂.

Of course, they are released in very small quantities into the atmosphere, only in the case of defective leak tightness of systems or in the case of poor recovery of scrapped obsolete equipment. However, they have an impact on the overall greenhouse effect that

can not be considered negligible.

All these gases could have been included in the Kyoto Protocol. However, CFCs and HCFCs were already banned within the framework of the Montreal Protocol and were excluded from the Kyoto Protocol.”

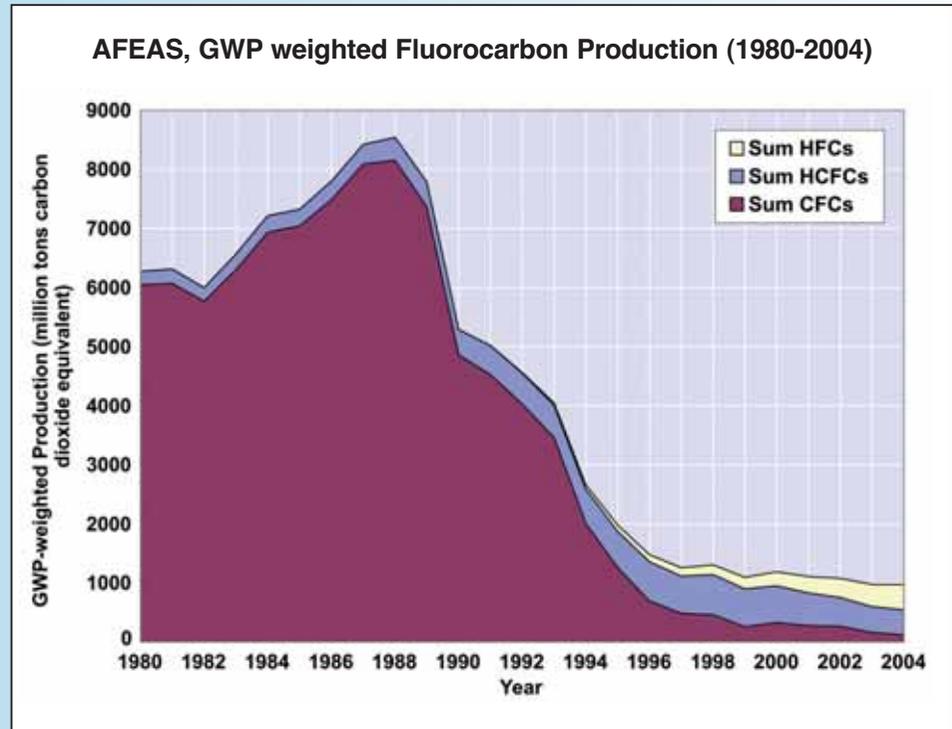
The production of CFCs has almost ceased, even if the recovery of banks of CFCs is still an important issue. They have been replaced by HCFCs which also have an ozone depleting and a global warming potential, but much lower, and by HFCs, which only have a global warming potential (GWP), similar to the GWP of HCFCs on the average. Thus, these replacements have made it possible to eliminate more than 25% of global greenhouse gas emissions compared to 1990. The efforts of the refrigeration sector have already had a significant impact both on ozone layer recovery and on the mitigation of global warming. There are thus two issues: the reduction of the direct effect of refrigerant emissions and the reduction in the energy consumption of the refrigeration systems, which use electricity (indirect effect).

The indirect effect is the most important one. It represents 80% of the global warming impact of refrigeration systems and 15% of worldwide electricity consumption.

MEASURES TO BE TAKEN

Reduction in energy consumption

The coefficient of performance (COP) of refrigeration systems has already been improved. For instance, in commercial refrigeration, it was about 2.5 in 1960, it is now about 4; new refrigerators use four times less energy in 2008 than 35 years ago. The IIR estimates that a reduction in the energy consumption of refrigeration plants by 20% by 2020 is still perfectly possible. However, it would be necessary to not only focus on the performance of each plant separately, but to consider the overall systems: reduction in the refrigeration needs by the performance of insulating materials, use of overall energy systems such as heat pumps both for air conditioning and heating... Refrigeration is just one part (even if it is a major part) of overall solutions leading to reduced energy consump-



tion in housing and transport.

Reduction in refrigerant emissions

Whatever the refrigerant used, it is first necessary to reduce, for safety and environmental reasons, leakage. The IIR's objective is to reduce refrigerant leakage by 30% by 2020 thanks to refrigerant containment (optimization of tightness...), particularly in mobile air conditioning and commercial refrigeration, thanks to refrigerant charge reduction (optimization of indirect refrigeration systems, micro-channel heat exchangers...); thanks to proper maintenance and servicing of refrigerating plants (regular controls, systematic recovery, recycling, regeneration or destruction of refrigerants); thanks to training available to all refrigeration practitioners.

It is secondly necessary to develop the technology and the use of alternative refrigerants which have a low global warming potential. Some of them already exist, the so-called "natural refrigerants", particularly ammonia, CO₂, hydrocarbons. They are competitive in most cases, even if technological developments are still necessary for certain uses. It is also possible to develop new "chemical" refrigerants, such as HFO-1234yf, which should be available in 2011 for air-conditioning applications. These old or very new refrigerants could replace HCFCs and HFCs.

It is also possible to develop other kinds of technologies, such as magnetic refrigeration or solar refrigeration, which certainly could be a solution in certain cases in the future.

CONCLUSION

A lot remains to be done. Incentives to reduce the environmental impact of human activities and particularly of the refrigeration sector will certainly be applied. These measures have to take into account the necessary role of refrigeration for human life and the increasing need for refrigeration, particularly in developing countries.

The first problem to be addressed is insufficient information on available technologies and present and future technological developments.

The International Institute of Refrigeration is a knowledge and research driven global authority with no commercial interest, which may help all countries in their efforts to achieve sustainable development in refrigeration.

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- (3) - The Role of Refrigeration in Worldwide Nutrition, IIR Informatory Note, in preparation.
- (4) - Le froid dans la problématique Energie et Environnement, Didier Coulomb, Revue Générale du Froid, juillet-août 2008.



UNEP UNITED NATIONS ENVIRONMENT PROGRAMME
INTERNATIONAL INSTITUTE OF REFRIGERATION
CENTRO STUDI GALILEO - ASSOCIAZIONE TECNICI DEL FREDDO

XIII EUROPEAN CONFERENCE ON

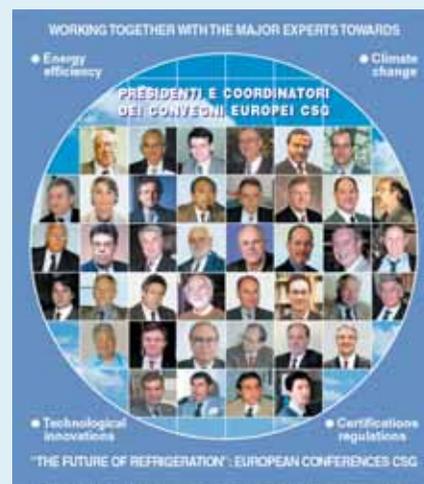
**TECHNOLOGICAL INNOVATIONS IN
 AIR CONDITIONING AND REFRIGERATION INDUSTRY**

**WITH PARTICULAR REFERENCE TO ENERGY AND ENVIRONMENTAL OPTIMIZATION, NEW REFRIGERANTS,
 NEW EUROPEAN REGULATION, NEW PLANTS, THE COLD CHAIN**

12th - 13th June 2009 - Politecnico di Milano

GENERAL CHAIRMEN

RAJENDRA SHENDE **Head, OzonAction UNEP DTIE**;
 FEDERICA FRICANO, ALESSANDRO PERU **Ministero dell'Ambiente e della Tutela del Territorio e del Mare**; ENNIO MACCHI, GIOVANNI LOZZA **Politecnico of Milano**; DIDIER COULOMB Director ALBERTO CAVALLINI Honorary President **International Institute of Refrigeration (I.I.R.)**; PATRICK ANTOINE President LOUIS LUCAS Past President **Association Française du Froid (A.F.F.)**; Honorary Director I.I.R.; THOMAS PHOENIX Vice-President **American Society Heating Refrigeration and Air conditioning Engineers (ASHRAE)**; MARK MENZER Senior Vice-President **Air-conditioning and Refrigeration Institute (ARI)**; REX BOYNTON President **North American Technicians Excellence (NATE)**; MARK LOWRY **RSES (USA)**; FRIEDRICH BUSH **E.P.E.E. (Germany)**; GERHARD NAUHAUSER President **Air conditioning and Refrigeration European Association (AREA)**; ALFREDO SACCHI President **Associazione dei Tecnici del Freddo (ATF)**; DENIS CLODIC Deputy Director **Ecole des Mines**; MICHEL BARTH President **Compagnie des Experts du Froid et de la Climatisation**; President **commission technique IFFI** - Honorary President **AFF**; PETER W. EGOLF President **Working Party on Magnetic Cooling - I.I.R.**; HERMANN HALOZAN **Graz University of Technology, Austria**; MARCO MASOERO **Politecnico of Torino**; ANDREA DE LIETO VOLLARO, FRANCO GUGLIERMETTI **University La Sapienza of Roma**; PAOLO AMIRANTE **University of Bari**; FRANCESCO ASDRUBALI **University of Perugia**; SERGIO BOBBO, ROBERTO CAMPORESE, GIROLAMO PANOZZO **I.T.C. CNR Padova**; FILIPPO DE ROSSI **Sannio University**; GIUSEPPE PANNO **University of Palermo**; FABIO POLONARA **University of Ancona**; LUCA TAGLIAFICO **University of Genova**



9,00 am - Friday 12th June 2009

GENERAL INTRODUCTION

**New regulations on F-gases and new refrigerants
 New plants with reference to energy and environmental optimization: D. Coulomb - R. Shende**

First Session

NEW REFRIGERANTS AND PERSPECTIVES

CHAIRMEN: **A. Cavallini** Università di Padova - I.I.R.; **R. Shende** OzonAction UNEP DTIE; **D. Coulomb** International Institute of Refrigeration; **L. Lucas, P. Antoine** Association Française du Froid; **H. Halozan** Graz University of Technology, Austria; **M. Menzer** ARI; **F. Bush** EPEE

Developments, perspectives and forecasts on new refrigerant plants and components. New synthetic and natural refrigerants, pure and mixtures (R134a, R404A, R507A, R407C, R410A, R417A, R422A, R422D) CO₂, ammonia, hydrocarbons; secondary refrigerants; New fluids: secondary refrigerant plants; ammonia, CO₂, absorption, hydrocarbon plants, Ice Slurry.

Speakers: R. Shende UNEP - **A. Cavallini** I.I.R. - **D. Coulomb** I.I.R. - **P. Antoine, L. Lucas** A.F.F. - **M. Menzer** ARI - **T. Phoenix** ASHRAE - **D. Clodic** Ecole des Mines - **P. Neksa** Sintef Energy Research (Norway) - **A. Pearson** IOR - **J. Morley** Du Pont (UK) - **E. Campagna** Rivoira - **H.V.D. Maaten** (NL), **G. Matteo** Honeywell - **C. Zilio** Università di Padova

Second Session

NEW COMPONENTS AND EQUIPMENT IN RELATION TO NEW ENERGY AND ENVIRONMENTAL ISSUES AND NEW REFRIGERANTS

RESULTS AND UPDATES IN NEW SYSTEMS

CHAIRMEN: C. M. Joppolo, G. Lozza, E. Macchi Politecnico di Milano; M. Barth Institut Français du Froid Industriel (I.F.F.I.); P. Egolf International Institute of Refrigeration; G. Neuhauser AREA
The magnetic cooling. The solar refrigeration and cooling with absorption plants. Renewable energy in air conditioning and refrigeration fields. New technology compressors and systems, new technology energy optimization, new components for household, commercial and industrial refrigeration. New technologies in air conditioning, refrigeration, process and design (legionella issue).

Speakers: L. Lucas, P. Antoine A.F.F. - E. Macchi Politecnico di Milano - P. Egolf I.I.R. - H. Halozan Graz University of Technology, Austria - F. Asdrubali Università di Perugia - H. Quack Dresden University, Germania - J. Süß Danfoss - G. Lozza Politecnico di Milano - M. Casini, G. Pisano, M. Dorin Off. Mario Dorin - E. Winandy (B), W. Bianchi Copeland - H. Renz, P. Trevisan Bitzer (D) - M. Zgliczynski, P. Valero Embraco - C. Angelantoni Angelantoni Industrie - P.A. Picard, F. Benassis AICVF-Climespace



9.00 am - Saturday - 13th June 2009

Third Session

OPEN DISCUSSION ON ENERGY EFFICIENCY

CHAIRMEN (open discussion): R. Shende OzonAction UNEP DTIE; T. Phoenix ASHRAE; A. Cavallini International Institute of Refrigeration I.I.R.; D. Coulomb International Institute of Refrigeration; M. Masoero Politecnico di Torino; F. Asdrubali - Università di Perugia; H. Halozan - Graz University of Technology, Austria

Discussion on energy issues in relation to the air conditioning, refrigeration and geothermal components and plants optimization. Discussion on energy saving and maintenance. European regulation on F-gases. Solar energy, heat pumps. Detection of refrigerant leaks; fluids recovery, recycling and destruction, energy efficiency; lubricants for synthetic and natural refrigerants.

Speakers (open discussion): R. Shende OzoneAction United Nations - F. Fricano - Ministero dell'Ambiente - D. Coulomb International Institute of Refrigeration - P. Antoine, L. Lucas A.F.F. - T. Phoenix ASHRAE - M. Menzer A.R.I. - F. Busch European Partnership for Energy and Environment - D. Clodic Ecole des Mines - R. Camporese ITC CNR di Padova - F. Benassis A.I.C.V.F. - M. Collantin consulente - M. Avraamides, European Commission - A. Chikouche Algeria



Fourth Session

EUROPEAN AND INTERNATIONAL LAWS, CERTIFICATIONS AND LICENCES IN REFRIGERATION AND AIR CONDITIONING AND ENERGY SAVING

CHAIRMEN: F. Fricano Ministero dell'Ambiente; R. Shende OzonAction UNEP DTIE; A. Cavallini I.I.R.; G. Nauhauser AREA; P. Antoine, L. Lucas Association Française du Froid A.F.F.; M. Menzer A.R.I. - F. Busch E.P.E.E

New F-Gas Regulation: Inspections, Logbook, handling refrigerants, minimum requirements for personnel and companies, trainings. European certifications and licenses, welding, brazing.

Speakers: F. Fricano Ministero Ambiente - M. Avraamides European Commission - G. Nauhauser AREA - F. Busch EPEE - M. Masoero Politecnico di Torino - P. Fantoni, A. Sacchi ATF - M. Serraino Politecnico di Torino - K. Berglof Climacheck - D. Prisco TUV Thuringen

Fifth Session

NEW CONTROL TECHNOLOGIES, THE COLD CHAIN COLD STORAGE AND TRANSPORT

CHAIRMEN: P. Amirante Università di Bari; G. Panno Università di Palermo; G. Panozzo ITC CNR di Padova; E. Fornasieri Università di Padova; A. Sacchi ATF - Politecnico di Torino; J. Guilpart Cemagref; G. Cavalier Cemafroid; G. Piola Assologica

New technology in the cold chain: cold storage, refrigeration preservation, insulation; applications to industry. New equipments and controls. Energy saving optimization in the cold chain. Environmental control in food processes and safety control in the cold chain: ATP.

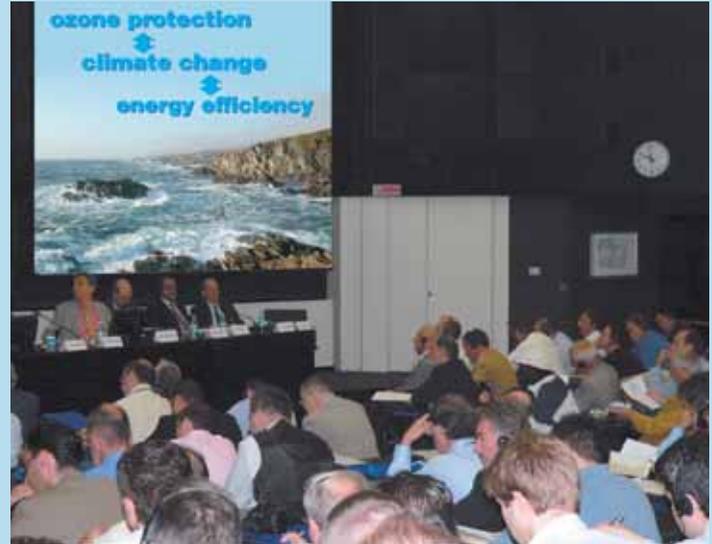
Speakers: G. Panno Università di Palermo - E. Fornasieri, L. Cecchinato Università di Padova - P. Amirante Università di Bari - G. Panozzo ITC CNR di Padova - T. Ferrarese Carel - M. Bassi Embraco - S. Da Ros Epta/Costan - D. Branchi Testo - A. Pianetti Georg Fisher - S. Iyama Bio Intelligence - A. Cavatorta consulente - A. Sacchi ATF - Politecnico di Torino

*General discussion with the participants
in the conference*

**WORKING TOGETHER WITH THE MAJOR EXPERTS TOWARDS
“THE FUTURE OF REFRIGERATION”: XIII EUROPEAN CONFERENCE 12th-13th JUNE 2009**



UNEP offices in Paris: from the left D.Coulomb-IIR, R.Shende-UNEP, M.Buoni-ATF, J.Curlin-UNEP.



The European Conference UNEP-IIR-CSG-ATF will be held in Milan on the 12th-13th June 2009: www.centrogalileo.it



Patrick Antoine AFF President.



The XIII European Conference about the latest technology in refrigeration and air conditioning with particular reference to the energy issues will be organized by CSG-ATF, by the United Nations Environment Programme-UNEP and by the International Institute of Refrigeration-IIR on the 12th-13th June 2009 in the Politecnico of Milan.



From the left Mark Menzer vice-president AHRI, Marco Buoni secretary ATF and on the right Stephen Yurek president AHRI.



The presidents of the major World Associations: (from the left) E.Buoni-CSG, A.Zoltan-HRACA, R.Berckmans and J.Jacquin-AREA, A.Cavallini-IIR, F.Billiard-IIR, R.Vallort-ASHRAE, D.Coulomb-IIR, A.Gac-AFF, R.Shende-UNEP, L.Lucas-AFF, M.Buoni-ATF.



On the right photo, the presidents of the XII European Conference in Milan who took part to the agreement UNEP-ASHRAE: Prof. Cavallini - Padoa University, K.Isa - Iseda Turkey, R.Shende - UNEP, E.Macchi - Polytechnic of Milan, T.Phoenix - ASHRAE, D.Coulomb - IIR, M.Buoni - ATF (www.centrogalileo.it)



Pietro Asinari - Marco Masoero

Trends in Commercial Refrigeration

PIETRO ASINARI - MARCO MASOERO - MICHELE CALÌ

Department of Energetics DENER - Politecnico di Torino - Italy

The Department of Energetics (DENER) of Politecnico di Torino (POLITO) is active since 1982 in research and consulting in most areas related to energy processes: energy planning and environmental impact assessment, renewable energy sources, hydrogen technologies and fuel cells, nuclear physics and engineering, automotive and aerospace propulsion, end-use efficiency in the residential, tertiary and industrial sectors. Teaching activities at the Bachelor, Master and Doctorate levels are provided by a staff of over 60 faculty members, active in the Engineering and Architecture schools of POLITO. In the refrigeration sector, DENER is currently conducting research on innovative systems for stationary, automotive and aeronautics applications, with particular attention to the employment of natural refrigerants such as CO₂. Cryogenics applications are also investigated as part of international research programs on nuclear fusion (ITER project). Another important line of activity addresses the efficiency of refrigeration equipment in air conditioning (Project Harmonac, funded by the EC within the framework of the EIE program) and the performance of reversible heat pump systems (Annex 48 of the IEA-ECBS program).

This article describes the trends of commercial refrigeration, with particular reference to experiences being carried out by industries and research institutions in the NW of Italy, in order to enhance the energy and environmental performance of equipment and components. In particular, a case study is discussed concerning the opportunities for aeronautical applications.

INTRODUCTION

Commercial refrigeration is an important segment in the food chain: it includes equipment such as vending machines that are common in most buildings open to the public, display cabinets for refrigerated or frozen food that are present in any store or supermarket, as well as refrigerated transportation.

In Italy, the main productive district for commercial refrigeration is located in the area around the city of Casale Monferrato, in the North-Western region of Piemonte, where about 20 different industries produce a full range of components and complete equipment for all typical applications. In order to face the commercial and industrial challenges posed both by globalisation and by environmental concerns, the refrigeration industry is developing a significant effort, involving the whole chain of product innovation, from design down to manufacturing and marketing, including the application to new sectors. This paper outlines some of the main

trends of design innovation, which are mostly significant in terms of energy efficiency and environmental performance; it also presents a new application in the aeronautics sector.

TECHNOLOGICAL AND DESIGN INNOVATION

The technological core of any refrigeration equipment is clearly placed in the thermodynamic process leading to the production of a useful cooling effect. At present, no viable alternatives to the classical vapour-compression inverse cycle seem at hand; performance enhancement of such cycles involves both the selection of the refrigerant fluid, as well as the optimisation of all system components: compressor, heat exchangers, expansion device, and controls.

The substitution of CFCs with the more ozone-friendly HCFCs and HFCs is now a well established practice in Europe, following the implementation in the year 2000 of the EU 2037 standard. The adoption of such fluids, however, has not completely solved the environmental problems associated with refrigeration, since HFCs still contribute to global warming: in response to such concerns, the recently introduced F-gas Regulations have set the obligations and practices to avoid accidental release of refrigerant fluids during system manufacturing, operation, maintenance, and phase-out.

As an alternative to synthetic fluids such as HFCs, a great deal of attention

has been devoted to natural refrigerants such as ammonia, hydrocarbons (HCs), and carbon dioxide (CO₂). Their use is already quite common for selected applications, e.g. HCs in domestic refrigeration and CO₂ in air conditioning systems for automotive or aeronautics applications. One barrier to the diffusion of natural refrigerants is the lack of international standards regulating their use; typically, a limit is placed on the maximum amount of refrigerant that the thermodynamic cycle may use, which leads to system fractioning at high cooling demand.

The transition to natural refrigerants obviously implies a substantial redesign of the main system components: in particular, CO₂ poses the most serious technological and design challenges. The heat transfer characteristics of CO₂ are better than for any other natural fluid, but still worse than for synthetic fluids such as HFCs. Furthermore, the transcritical nature of the CO₂ refrigeration cycle implies a thorough redesign of both the compressor and condenser, due to the extremely high operating pressures (on the order of 100 bar) and to the fact that the heat rejection process takes place in liquid phase, with temperature excursions that may exceed 100°C, rather than in a constant-temperature phase-change process.

An essential role in CO₂ cycles is played by controls. An optimal maximum operating pressure in fact exists for any evaporating condition determined by the specific type of application. This implies the use of more

sophisticated pressure regulating devices, capable of tracking the optimal pressure differential for varying operating conditions.

A central role for a successful operation is played by the compressor. A key factor is the fluid tightness, which becomes critical at such high pressures: for commercial applications hermetic compressors are preferred to semi-hermetic ones, which are customarily used in the automotive and aeronautics sectors.

Even in the case of conventional fluids, innovation in controls may substantially help increasing the energy performance: it is the case of variable-speed compressors, based on inverters that are already common in large industrial refrigeration plants and in air conditioning, and are now appearing also in new commercial units.

Further down the line are more radical innovations - such as Peltier-effect or ejector-cycle refrigeration - that however still require a substantial R&D effort in order to assess their industrial feasibility.

The energy performance enhancement of a commercial refrigeration system is also determined by the reduction of its cooling load: this implies a better thermal insulation of the glazed and opaque envelope, the control of unwanted outdoor air infiltration, and a better efficiency of the lighting systems placed inside the refrigerated compartment.

Transfer of technologies that are already well established in the building sector is one possible way for achiev-

ing this goal: using high performance glazing with U-values as low as 1.1 W/m²K in place of conventional double glazing (U = 3 W/m²K), controlling air infiltration with air barriers in open display cabinets, and substituting conventional fluorescent lamps with more efficient LED systems or with external light sources equipped with optic fibres to channel the light inside the refrigerated space, are a few examples of such technologies that may be successfully applied to commercial refrigeration.

The thermal insulation of the opaque walls is now typically made with expanded polyurethane foam. This solution has several advantages - namely, ease of production, low costs, and high thermal performance - but one serious disadvantage: being polyurethane a thermoset resin (rather than a thermoplastic one), it may not be recycled.

This problem leads us into another fundamental aspect of the environmental performance of commercial refrigeration equipment: what to do when they are phased out (the problem is particularly relevant, due to the much shorter operating life of a commercial refrigerator - typically 2-3 years - compared to a domestic one). Today, phased-out units are disassembled: the refrigerant fluid is recovered, the compressor is extracted and molten (with the lubricant fluid still inside), valuable heat exchanger materials (aluminium and copper) are recovered together with glass and the metal sheets that make up the external envelope, while polyurethane is subjected to grinding and successive disposal as a waste.

In order to minimise the waste disposal problem and the environmental performance in more general terms, Life Cycle Analysis techniques may be applied, leading to a more effective "Cradle-to-Grave" design process, in which the equipment is conceived by taking into account not only its performance during operation, but also the energy costs of construction and the possibility of complete recovery of the materials after phasing out.

A sector that shows very promising potential for technological innovation is refrigerated transportation, which includes short-range distribution of fresh products (e.g. fruits and vegeta-



Politecnico of Torino, where Centro Studi Galileo, has been organizing for years trainings and conferences about refrigeration and air conditioning.

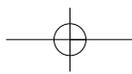


Figure 1.
The portable experimental test rig TWIN-CO₂.



Figure 2.
Detail of the double compressor unit of the test rig TWIN-CO₂.



bles, dairy products, etc.) as well as long-range transportation of refrigerated or frozen food that must be conserved for weeks. The main innovative trends concern the design of the evaporator (e.g. the use of finned-tube forced-convection compact heat exchangers) and the adoption of pas-

sive refrigeration systems (PRS). PRS makes use of phase-changing materials (PCM), typically eutectic salts, to accumulate a sufficient amount of refrigeration energy that is subsequently released over the time required to maintain the desired temperature level in the refrigerated compartment.

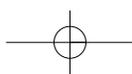
This concept may be used in principle for any type of application, but is particularly interesting for long-range (up to 30 days) storage, as an alternative to the conventional reefer containers, in which the complete refrigerating unit (compressor included) is mounted on board: with PRS containers, the cooling system is initially “charged” with a dedicated unit, the refrigerated container only is shipped, while the refrigerating station remains ashore. A further advantage of this concept is that the PCM remains at a temperature very close to that of air: this avoids an excessive dehumidification of air, reducing dishydration and weight loss of the foodstuff, as well as the

need of defrosting of the heat exchanger.

COMMERCIAL REFRIGERATION GOES ABOARD

The previous outline clearly shows the opportunities for innovation in the commercial refrigeration sector. The cooperation with public scientific institutions appears to be a promising formula for developing industrial research partnerships that may be mutually beneficial for the academic as well as the industrial world. In the following, a case study is discussed concerning the opportunities for aeronautical applications.

In the aircraft industry, the term Environmental Control System (ECS) is used to identify the devices realizing suitable environmental conditions for passengers and crew inside the cabin [1]. In the commercial transport aircrafts, air-cycle air conditioning for the ECS represents the largely predominant strategy. This strategy is usually a matter of convenience due to the



easiness of installation and extraction of compressed air from engine bleed ports, but it enormously increases the energy consumption for air-conditioning.

For the latter reason, the traditional picture of the ECS is nowadays under discussion. In fact the goal of reducing energy consumption due to transportation is considered a top priority issue and it will affect the aircraft industries in the next years by forcing the development of new technological solutions. Many research and development programs have been funded in order to reach this goal [2].

According to other mobile applications, for example automotive and marine applications, some evidence exists about the fact that a more widespread electrical power distribution would allow us to consider more efficient components and a more flexible management of the energy demand. Improving electrical power distribution and increasing the number of the electrical systems can also open some new opportunities for the ECS. In particular, compressors driven by electrical motors can be used in a more efficient Vapor Compression System (VCS).

Concerning the working fluids, the natural fluids should be considered in order to avoid any future regulation constraint, as it happens now with HFCs (like the well known R134a) which do not deplete the ozone, but still significantly contribute to the atmospheric warming. Among the nat-

ural fluids for refrigeration, carbon dioxide seems suitable for this application. First of all high working pressures in refrigerant cycles based on carbon dioxide imply a reduction of the refrigerant charge and consequently more compact compressors and lighter machines.

Secondly the thermophysical properties of carbon dioxide are favourable to produce high heat transfer coefficients in the heat exchangers of the equipment (of suitable geometry), often higher than those commonly obtained with traditional synthetic refrigerants [3-4]. Finally carbon dioxide is a product that displays no special local safety problem, as it is non-flammable and non-toxic in the concentration recommended for the ECS application.

RESEARCH PROJECTS

In order to understand which constraints limit the design process and which configuration yields the best performance for the transcritical refrigerating cycles based on carbon dioxide, some on-ground experimental tests have been performed in the past, particularly dealing with the airborne application [5]. However, even though these tests allow us to check the practical performances of this technology, they are not suitable to catch the actual peculiarities of the in-flight operating conditions. For this reason, the administration of Regione Piemonte, in collaboration with Politecnico di Torino, has funded an in-flight testing of a refrigeration prototype based on carbon dioxide installed on a small civil aircraft.

Moreover the transcritical cycles based on carbon dioxide offer the opportunity to deal quite efficiently with the on-board heating load, which is particularly relevant at cruise conditions. Within the project Research & Development for the Aeronautical Sector (Progetto per lo Sviluppo e l'Innovazione del Settore Aerospaziale - SISA), a pool of universities of Regione Piemonte in Italy has investigated new technological opportunities for the next generation aircrafts. In particular, the Politecnico di Torino has developed an innovative prototype,

called TWIN-CO₂, in collaboration with the Italian company Mondial Group s.r.l., for investigating the performances of a reversible heating/refrigerating machine based on transcritical carbon dioxide (see Figures 1 and 2). The system essentially consists of two twin carbon dioxide systems: the first one for simulating the winter environmental conditions all around the year, and the second one for working as heat pump, with tunable operating conditions. The test rig is completely portable for being used a demonstrator and it may help in pursuing the goal of promoting the diffusion of this technology.

CONCLUSIONS

The demand for more environmentally friendly and energy efficient commercial refrigeration systems has proved to be a formidable stimulus in this important industrial sector. New actors from emerging countries are appearing on the market, and this is a further reason for pushing on innovation for companies operating in countries, such as Italy, which have a well established industrial tradition. The cooperation with public scientific institutions appears to be a promising formula for developing industrial research partnerships that may be mutually beneficial for the academic as well as the industrial world.

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Centro Studi Galileo organizes periodically European Conferences about "New Technology in Refrigeration Industry" both in Politecnico of Milan and Politecnico of Turin (in the picture), in which Prof. Masoero has been many times President.



Alberto Cavallini

Heat pumps using natural working fluids: an environmental friendly solution

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The University of Padova was founded in 1222 and comprises many Faculties; at present about 65,000 students in several subjects with more than 2000 teachers are attending the University of Padova.

Within this, the Dipartimento di Fisica Tecnica of the Engineering Faculty gets together 20 teachers and research workers.

The research activities of the Department are devoted to thermodynamics, heat transfer, refrigeration technology, heat pumps, air conditioning, renewable energy, thermodynamic properties of refrigerants, applied acoustics.

Heat pumps and reversible units are considered as a viable solution for the reduction of primary energy consumption in heating and refrigerating applications.

In this paper water-heating heat pumps operating with transcritical carbon dioxide vapour compression cycle are considered. For this particular application the market looks promising, especially in Japan where the Government, thanks to a favourable legislation, forecasts that the installed units in 2010 will be around 5 million.

With regard to hydrocarbons, the use of

propane as the refrigerant in heat pumps is reviewed. The main problem related to the adoption of hydrocarbons is their flammability, which has prevented their use in large scale. Additional safety restrictions are then required and, since the possible hazards depend on the total amount of refrigerant trapped in the system, the charge minimization is a major design constraint. Some technological results are reported in the present paper, with particular focus to the charge reduction.

Key Words: heat pumps, carbon dioxide, hydrocarbons, heating/cooling systems

INTRODUCTION

In the last years a strong research activity has been carried out in research institutions and in forward-looking refrigeration companies for the development of high efficient heat pumps operating with fluids not harmful to the environment. Having the TEWI concept as the benchmark, the optimization target is to reduce as much as possible both the "direct impact", that is the effect of the refrigerant when released into the atmosphere, and the "indirect impact", that is linked to the equipment's efficiency. The development of efficient heat pumps working with "natural" fluids seems to be the ultimate solution. Based on this technological roadmap, two options are here considered, with reference to different fluid categories: carbon dioxide and hydrocarbons.

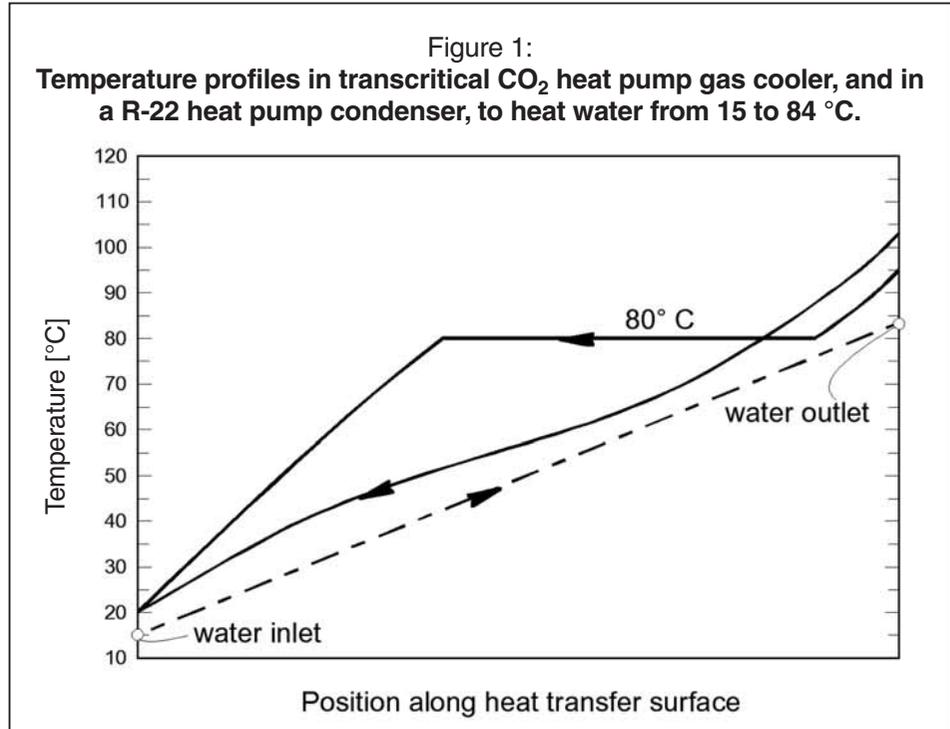
CARBON DIOXIDE TRANSCRITICAL HEAT PUMPS

Since Gustav Lorentzen milestone work (1993), that can be considered the "manifesto" of the "modern" use of CO₂ as a refrigerant, several applications have been investigated to prove the workability of the new "transcritical" technology. Among the most promising applications it is worth mentioning the following: heat pumps and water heaters, mobile air conditioning, commercial systems, industrial refrigeration (both transcritical and cascade), secondary coolant applications.

Thanks to much academic research work, supported by a group of interested industrial partners, the technological feasibility of the proposed "revival" of carbon dioxide is now demonstrated and now the efforts are devoted to enable the technology itself to compete in the market. From this standpoint, extremely promising appears the market for CO₂ heat pump water heaters, especially in Japan, where the Government, thanks to a favourable legislation, forecasts that the installed units in 2010 will be around 5.2 million.

The U.S. company Carrier, within the United Technologies Research Centre (Huff and Sienel, 2006), has developed a series of commercially sized CO₂ heat pump water heaters now installed and operating into a diverse range of geographic and application sites across the USA. The field tests have indicated quite promising results in terms of system performance, relia-

bility, customer value Visser (2008) calculated that the use of CO₂ reversible chillers (HP) for American office buildings in climate like Sydney (Australia) would lead up to 63% primary energy consumption reduction. In a transcritical CO₂ refrigerating cycle, the considerable amount of exergy made available in cooling the hot dense gas in the gas cooler is completely dissipated by transferring heat to the ambient cooling medium (whether ambient air or water). Whereas, when the transcritical cycle is exploited as a heat pump, part of this same exergy, transferred to the heated medium, makes up just the effect looked forward to. In this case the equipment energy efficiency can be competitive or often higher than the one obtained with machines of the same type operated with traditional refrigerants. The same conclusion can of course be drawn with respect to refrigerating machines with heat recovery at the transcritical gas cooler. The shape of the constant pressure lines above the critical point for CO₂ makes it clear why transcritical cycles very well lend themselves to heat pumps for sensible heating of a mass flow rate of a fluid through a high temperature change. And the value of COP is not much dependent on the maximum temperature of the heated fluid. As an example, Fig. 1 illustrates the excellent matching between temperature profiles of CO₂ at 120 bar and a water flow heated from 15 to 84 °C in the counter-current gas cooler. The same Fig. 1 illustrates also the definitely less favourable temperature profile required in the condenser of a heat pump run with R-134a to accomplish the same duty. Both working fluids processes in the heat pumps are determined with reference to simple vapour compression cycles. The conditions are: suction of dry saturated vapour at 0 °C (evaporation temperature), compression isentropic efficiency $\eta_{ic}=0.80$, with the constraint that in the counter-current heat exchanger (water heater) the local temperature difference between working fluid and water never be less than 5 °C. Similar results were exploited both experimentally and numerically by Fernandez et al. (2008). In comparison with traditional heat



pumps for residential heating, CO₂ transcritical heat pumps, at comparable capacities, lend themselves to heating a smaller air mass flow rate through a larger temperature lift, with fewer problems for cold droughts in the heated rooms.

On the contrary, the application of CO₂ transcritical heat pumps associated with the traditional European radiator heating circuits, with water temperature change of only 20 °C (for example, from 50 to 70 °C), does not prove energy competitive against gas boilers. Stene (2008) demonstrated that by using a counterflow tri-partite CO₂ gascooler in combination with an external single-shell hot water tank and low-temperature heat distribution system contribute to reach high COP values in integrated residential heat pumps systems.

It is well known that in normal operating conditions, the CO₂ transcritical cycle must be operated at optimum gas cooler pressure. Under extreme outdoor conditions, the cycle can be operated at above-optimum pressure, with an increase in the heat output (or, conversely, keeping the gas cooler pressure constant when the evaporating pressure tends to decrease). In this way, it is less necessary to resort to supplemental heating (often performed with electrical heaters), and therefore without heavily penalising the seasonal

energy efficiency of the plant. The CO₂ transcritical cycle is characterised (even when operated at optimum gas cooler pressure) by a reduced influence of evaporating temperature on heating capacity and coefficient of performance COP. At low environmental temperatures, it retains high heating capacities (which can be further increased, as already mentioned, by raising the gas cooler working pressure). From what discussed above, one can conclude that the seasonal energy efficiency of a CO₂ heat pump, as compared to a standard machine, can turn out to be more favourable throughout the full heating season, even if energy performance at strict design conditions may prove lower. It is always necessary to carry out an extended analysis, taking into account the different operative conditions and the associated working times, considering also energy consumption of system auxiliary components (and in particular, of the different fans), and of the necessity of supplemental heat, to draw really consistent conclusions.

PROPANE HEAT PUMPS

The use of hydrocarbons is a good opportunity to develop environmentally friendly HVAC equipment, since the direct effect of the refrigerant on the

anthropogenic global warming is almost completely avoided, while the indirect effect can be reduced by exploiting the favorable thermodynamic properties of these fluids.

In the case of large systems for heating and cooling of buildings, such equipment could be situated in a machinery room or outside in the open air (for example on the roof of the building) in order to provide some kind of intrinsic safety. In this case, an indirect system can be used: all the components containing refrigerant could be situated outside, or in a machinery room. Indirect systems can be well inserted in ground-source heat pumps.

Corberan et al. (2008) reports the performance study of a reversible water to water heat pump working with propane (R290) and designed for a nominal cooling capacity of 16 kW. A semihermetic compressor was employed for their propane machine since no compressor manufacturer allows for the moment the use of scroll compressors with flammable refrigerants. An electronic expansion device has been employed: it incorporates the saturations curves for propane and has shown to be able to keep a very constant superheat. Brazed plate heat exchangers were used as the condenser and the evaporator. Their prototype gave excellent performance on both cooling and heating modes with higher COP in comparison with the reference R407C unit: even though a semihermetic piston compressor was employed instead of the original scroll compressor, the propane equipment is still able to provide a higher COP for the whole range of application. This unit, especially designed to minimise the refrigerant charge, is able to provide around 17 kW with only 550 g of propane.

The charge inventory minimization is in fact a major design objective for equipment using flammable fluids like hydrocarbons. The use of an indirect system with secondary fluid loops drastically reduce the charge inventory when compared to direct systems. At level of components, heat exchangers specially designed for low charge can allow a significant charge reduction. Plate heat exchangers can be considered the current industrial benchmark in charge minimization for liquid-to-refrigerant

condensers and evaporators. However, minichannels technology appears to be a very good opportunity to further minimize the charge without loss in energy performance.

In Fernando et al. (2004) a water-to-water heat pump with a heating capacity of 5 kW was tested. Their system was designed to minimise the charge of refrigerant mainly by use of minichannel aluminium heat exchangers. It was shown that the system could be run with 200 g of propane at typical Swedish operating conditions without reduction of the COP compared to a traditional design.

A new 100 kW heat pump using propane as the working fluid and devoted to laboratory tests has been designed and tested at the University of Padova, in the framework of the European project SHERHPA. A description of the unit, with a safety analysis, is reported in Cavallini et al. (2007). Two conventional brazed plate heat exchangers, an evaporator and a condenser, are installed in the equipment together with low charge shell-and-tube heat exchangers using 2 mm i.d. minichannels. In Del Col et al. (2008), the configurations using the minichannel condenser have been compared to the configurations using the brazed plate condenser, both in terms of energy efficiency and refrigerant charge. While the difference between the measured heating capacities and COPs is negligible, as far as the charge is concerned, around 0.8 kg refrigerant charge reduction is obtained when using the minichannel condenser. This same heat pump was also tested using an internal minichannel heat exchanger to increase the superheat, as required by the manufacturer of the semi hermetic reciprocating compressor.

Since five heat exchangers have been installed in the present heat pump, the piping length could not be minimized. By reducing the length of the piping, the authors claim that their heat pump could be run with around 3 kg of propane when using the PHE condenser and the PHE evaporator. The use of the minichannel condenser allows a further 25% charge reduction. Further charge reduction would require the reduction of the amount of oil in the compressor.

SUMMARY

An extensive research effort has been devoted in the last years to show the feasibility of carbon dioxide transcritical cycles, leading to promising results in terms of energy efficiency for water heater applications and an increasing market seems possible for such equipment. Recent papers indicate that suitable hydronic system arrangement can make possible the use of CO₂ heat pumps also for residential heating and air-conditioning. However, the demand for space heating and cooling may be more suitably addressed using hydrocarbons reversible heat pumps. In this case, the refrigerant charge minimization represents the most important target to cope with flammability. An indirect system using minichannel heat exchangers seems to be an appropriate solution for reaching high energy efficiency with low refrigerant charge. Further improvements and new solutions to increase market competitiveness of natural refrigerant heat pumps are yet to come.

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Ground-source heat pumps

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At the Institute of Thermal Engineering, Head Prof. Juergen Karl, advanced steam generators - especially fluidised bed technology - and conventional power plants, mainly CO₂- free power plant technologies, are key aspects. The area Decentralized Energy Systems and Biomass concentrates on innovative solutions for gasification technologies, Stirling engines and second generation fuels and fuel cells. In the area Heating, Refrigerating and Air Conditioning, Prof. Rene Rieberer, advanced HVAC systems, mobile air conditioning, sorption technologies and testing of low environmental impact refrigerants are the main topics. The area Energy-Efficient Buildings, Prof. Wolfgang Streicher, develops energy strategies and software solutions for the optimisation of residential and commercial buildings.

The ground is a heat sink/heat source, which is, similar to outside air, almost not limited by availability. Limitations can be the ground temperature in very hot regions and the composition of the ground. In cold regions with mainly heating demand ground-source systems are dominating the market, but the share of systems for cooling is also increasing. A completely different use of the ground happens in the case of large systems with both cooling and

heating demand: natural recharging of the ground no longer works, and an excellent solution is to use heat removal from cooling operation. The ground becomes a store, and the temperature changes in this store are the result of heat extraction/heat removal over the year. Taking all these aspects as a whole highly efficient systems can be realised.

Key Words: *ground-source heat pumps, buildings, heating/cooling systems*

INTRODUCTION

First considerations to use the ground as a heat source were made in 1912 by Zölly from Switzerland. However, the commercial utilisation of the ground as a heat source/heat sink for heat pumps began in the Seventies after the first oil price shock. The systems installed at this time were mainly secondary loop systems. Later on, direct-expansion systems have been introduced (Sanner, 1992).

The ground acts as a seasonal storage. At a depth of about 10 m the undisturbed ground temperature remains constant over the year. Between the table with constant temperature occurs and the surface, the ground temperature changes due to the outside conditions; depending on the depth, these changes are damped and delayed. Eliminating peaks of the outside air temperature, the ground is an efficient heat source/heat sink for heat pumps. Ground source heat pumps can be

applied for different climates, different ground properties, for small and large systems, and for heating-only as well as heating and cooling applications (Halozan and Rieberer, 2007).

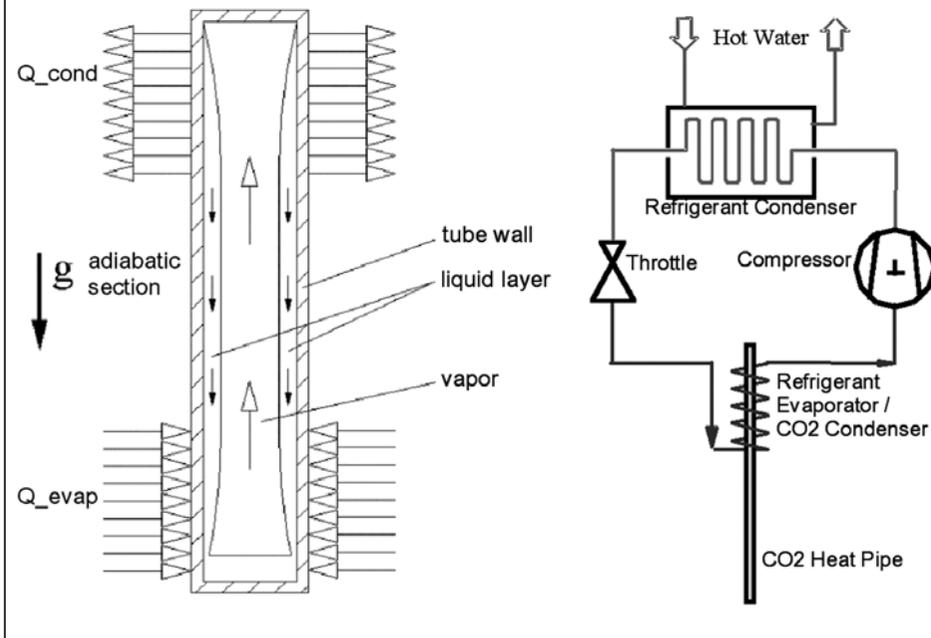
The common characteristic of small systems is natural ground recovery, mainly by solar radiation collected by the ground surface. Small systems are in use for heating as well as heating and cooling, they can be used for direct cooling (without heat pump operation), at least at the beginning of the cooling season. For large system recovery of the ground has to happen by heat removal and heat extraction. Sometimes additional systems for recharging the store have to be provided, hybrid systems have to be designed.

HEATING-ONLY SYSTEMS

For the utilisation of the ground as a heat source for heating-only operation various system designs have been developed; the differences are mainly caused by the capacity of the system and the area available.

Horizontal ground coils are most commonly installed at a depth of about 0.3 m below frosting depth, i.e. in the populated regions of Austria at a depth of about 0.8 - 1.2 m. At the beginning of the heating season the ground temperature is higher than the undisturbed ground temperature (15 to 19°C instead of 10 to 12°C); during the heating season it drops below 0°C caused by heat extraction, but moisture migration to and frost formation

Figure 3:
Working principle of a heat pipe (two-phase thermosyphon) and heat pump system layout



around the coil help to stabilise the temperature. At the end of the heating season natural recharging starts and heat is delivered from the surface to the coil; if the system design is correct vegetation above the coil is hardly influenced at all.

Vertical wells are required if the surface area available is insufficient for horizontal systems. In the case of vertical wells, two designs are possible, either shallow wells to a depth of 20 m or deep wells down to 100 m or more (250 m). The depth depends on the ground conditions and on the drilling equipment available.

The heat exchangers are either of the U-tube and double U-tube type, or of the coaxial type. Other versions of ground heat exchangers are the slinky collector, the ditch collector, and spiral heat exchangers for bore holes with larger diameters as developed by O. Svec, Canada.

The systems installed world wide are most commonly secondary loop systems. Besides these secondary loop systems, which dominate globally the application of ground-source heat pumps, direct expansion systems have been developed, and especially in Austria a great share of the installed heating-only ground-source heat pumps use this technology.

In the case of secondary loop systems the heat pump unit and the heat extraction system are separated. The heat pump unit is being designed as a compact brine/water unit, where the refrigerant content can be minimised and which can be manufactured and tested in the factory to fulfil the requirements of leak tightness.

The problem of this concept is the secondary loop system: The heat carrier, most commonly a glycol/water mixture, has to be circulated through the ground coil by means of a circulation pump sized for the lowest temperature which may occur. Each temperature drop has a negative influence on the COP, i.e. the power requirement rises and increases the indirect greenhouse gas emissions due to increased drive energy generation.

Direct expansion systems have some advantages compared with secondary loop systems: The evaporator of the heat pump unit is directly installed in the ground, which means that the heat transfer from the ground to the refrigerant takes place directly. The drive energy for the circulation of the refrigerant in the evaporator comes from the compressor and from the throttling loss, respectively; this means that no additional power for a circulation pump is needed.

This means that in the case of an appropriate design direct expansion systems are more efficient than secondary loop systems. The SPF of direct evaporation systems in new well insulated buildings with specific heat loads below 60 W/m^2 equipped with low-temperature floor heating systems are in the range of 4 to 5, 2 monitored systems achieved more than 6.

But there are also some disadvantages of direct-evaporation systems: Soldering at the site is (was!) necessary to connect the ground collector and the heat pump unit, refrigerant losses and pollution of the ground water can occur. The ground coil evaporator becomes much larger than the evaporator of a compact heat pump unit, thus the refrigerant charge increases. However, these disadvantages have been solved by manufacturers and installers of direct-expansion systems (Halozan and Rieberer, 2002).

An interesting development has been carried out by K. Mittermayr of the M-tec company, who developed a heat-pipe based ground probe with CO_2 as working fluid for vertical wells down to a depth of about 100 m (Rieberer and Mittermayr, 2001).

This self-circulating system is environmentally fully acceptable - the working fluid is CO_2 and the probe works oil-free - and it has the advantage that no circulation pump is required. The heat pump cycle is physically de-coupled from the heat source cycle, the CO_2 cycle (Fig. 1).

In general, new buildings get a better thermal insulation and the heat loads are reduced significantly. A further step has been already realised in the so called passive houses, ultra-low energy houses: The transmission losses through the building envelope are in the range of 10 to 15 W/m^2 . Such buildings can be heated using a controlled ventilation system consisting of a ground air collector, a heat exchanger and a heat pump. The fresh air is preheated in the ground air collector and the heat exchanger and then end-heated by the heat pump. The exhaust air is cooled in the heat exchanger and in the evaporator of the heat pump.

A further improvement can be achieved by using a ground coil for avoiding frosting/defrosting losses of the heat pump. SPFs achievable with such sys-

Figure 2:
Pile System

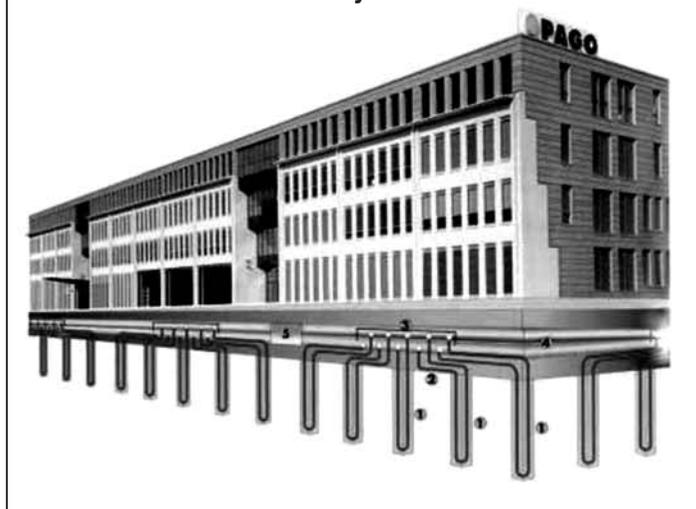
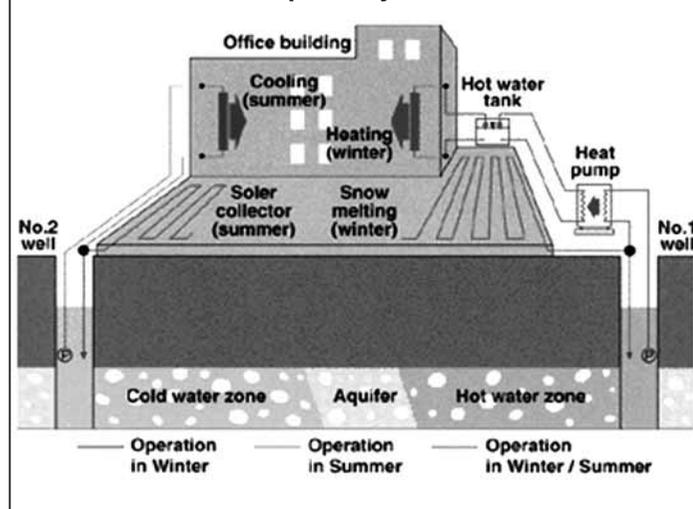


Figure 3:
Aquifer System



tems using a heat pump with CO₂ as working fluid are about 6. This seems to be the solution for low heating-energy buildings (Rieberer and Halozan, 1997).

HEATING AND COOLING SYSTEMS

The need for air conditioning depends not only on the climate, it also depends on the size of the building and the utilisation of a building; an additional point is architecture, glass is modern, and solar gains can become very fast solar loads, which have to be removed.

There are three types of climates which require air conditioning, climates with daily average temperatures higher than 24, climates with a humidity higher than 65 %, and climates, which combine both. In large commercial buildings high internal loads due to people, lighting, computer equipment etc. occur; these loads have to be removed also.

Secondary-loop ground-coupled heat pumps offer the possibility of both heating and cooling, and for this operation the ground is used as store made accessible by vertical bore holes, by pile systems (Fig 2), if piles are required for the foundation of the building, or aquifers (Fig 3).

Heat rejected during summer operation increases the ground temperature for heating operation, and heat extraction during winter offers the possibility of direct cooling without heat pump operation, only by utilising the heat

carrier, at least at the beginning of the cooling season. Later on only dehumidification may be carried out with the heat pump. This means that cooling and heating energy can be stored on a seasonal basis.

Using low-exergy systems can improve the energy efficiency of such a system further. Low-exergy systems means heat distribution systems with low temperature requirements for the heating season like floor heating systems and relatively high temperature requirements for the cooling season like cooling ceilings or activated concrete structures, the overall efficiency of buildings can be increased remarkably. To get efficient systems the cold water temperature has to be kept as high as possible and the hot water temperature as low as possible.

For dehumidification 6 °C to 8 °C are necessary; removing the cooling load can be carried out with temperatures of 16°C and higher. In such a case two heat pumps have to be used, one producing cold water with a temperature of 6°C to 8°C for dehumidification and a second producing cold water with a temperature of 16 °C to 20 °C for removing the cooling load, both combined with a ground store. Another approach is to use for dehumidification a DEC system, where the regeneration of the desiccant is carried out with the excess heat from the heat pump providing cold water for removing the cooling load. With such a concept highly efficient systems can be realised.

SUMMARY

Ground-coupled heat pumps gain importance world-wide with respect to energy efficiency in heating and cooling operation. The ground acting as a storage offers the possibility of damping the effects of the outside air temperature fluctuations, in colder climates it enables monovalent heating operation of the heat pump, and for utilities it is a tool for demand side management measures. New developments like improved heat pump units, advanced direct-expansion heat pumps or heat pumps combined with heat pipe based vertical probes show that there is still room for new ideas, which may be necessary for being competitive and successful in the future.

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Patrick Antoine

Phase-out of HCFCs: impact on air-conditioning and refrigeration systems operating on R22

PATRICK ANTOINE, GUY-NOEL DUPRÉ

President Association Française du Froid AFF - Uniclimate

The French Association of Refrigeration (AFF), together with the International Institute of Refrigeration, founded in 1908, is celebrating its 100th anniversary and it is well known for the important initiative carried out both at a national and at an international level. The issue of new refrigerants has often been analyzed by AFF and its previous presidents Mr. Louis Lucas and Mr. Michel Barth, especially during the European Conferences organized by Centro Studi Galileo and with publications of interviews, articles and documents in the magazine *Industria & Formazione*.



The seat of AFF is the historical building founded by Napoleon in 1801 as the first society for industrial promotion, in the historical square of St. Germain des Près.

The Montreal Protocol, within the framework of ozone-layer protection, limits the use and production of HCFCs according to the following time frame:

- Year 2000: ban on charging of new equipment;
- Year 2010: ban on recharging with virgin HCFCs;
- Year 2015: ban on recharging with recycled HCFCs.

With the 2010 deadline just a matter of months away, the ban on recharging with virgin HCFCs means that all chemical firms will have to stop manufacturing these refrigerants. As a result, only HCFCs derived from recovery will be available for maintenance purposes enabling existing air-conditioning and refrigeration equipment to remain in use.

In France, the Montreal (ozone layer) and Kyoto (greenhouse gases) Protocols have been legally adopted at a national level and tightness control is subjected to objectives. The French regulations are as follows:

- Decree No. 2007-737 of May 7, 2007 concerning certain refrigerants used in refrigeration and air-conditioning equipment (published in the Official Journal of the French Republic on May 8, 2007).
- Decree of May 7, 2007 concerning the tightness control of elements ensuring the containment of refrigerants used in refrigeration and air-conditioning equipment (published in the Official Journal of the French Republic on May 8, 2007).

This regulation will be completed by 4 orders:

– Order concerning the providing of certificates governing the ability of operators as foreseen in Article 13 of Decree No. 2007-737 of May 7, 2007; (*this is the Decree of June 30, 2008 published in the Official Journal of the French Republic on July 18, 2008*).

– Order concerning the approval of organizations foreseen in Article 15 of the Decree No. 2007-737;

– Order concerning the annual statement to be provided by authorized organizations, distributors of refrigerants, manufacturers of refrigerants and equipment containing refrigerants;

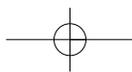
– Order concerning the frames of reference for professional skills related to the types of activities performed and the types of equipment used, including the conditions under which certificates governing competence are provided.

A major issue has yet to be resolved: will the recovery of R22 provide sufficient quantities to enable all existing equipment to continue to operate? In France, existing equipment contains a total of 25 000 tonnes of R22, and recovery provides 300 tonnes per year. This means that the leakage rate would have to be about 1% in order to offset losses through recovery. In fact, the current leakage rate is roughly 10%.

Users of equipment operating on R22 have several options:

- to carry on using R22 but to control the tightness of the equipment by minimizing all leakage;
- to envisage retrofitting in order to use another refrigerant;
- to replace the equipment.

UNICLIMA's advice on how to plan



Retrofitting solutions enabling another refrigerant to be used are as follows:
 - **HFCs** (hydrofluorocarbons): the pure refrigerants R134a and R23 for low-temperature applications

Mixtures obtained primarily with HFCs: R32, R125, R134a, R143a and R152a, with a few % hydrocarbons in certain mixtures.

Advantages of HFCs

- Safe refrigerant (A1)
- Zero ODP
- Compatibility with Cu and Al
- Availability of components

Drawbacks of HFCs

- GWP is often high
- Subjected to the F-gas regulation
- POE oil
- Joint behaviour

- **Ammonia: NH₃ or R717**

Advantages of NH₃

- Zero ODP and GWP
- Very well-known refrigerant
- Thermodynamic characteristics

Drawbacks of NH₃

- Toxic and flammable

- **CO₂ or R744**

Advantages of CO₂

- Safe refrigerant (A1)
- Zero or low ODP (1)
- Capacity

Drawbacks of CO₂

- Triple point (high), critical (low)
- High pressures

The refrigerating capacity developed is slightly greater and the COP is lower. The capacity of the condenser and the compressor unit may be insufficient.

Replacement of oil using a POE oil. Experience in flooded plants using a refrigerant with marked glide (Isceon range, R407C) should be borne in mind?

R410A has good features but would be difficult to envisage in this context because of the high condensing pressures.

Direct-expansion installations

(applications below 0 °C)

R404A and R507 can be suitable for these applications, provided that the above-mentioned precautions are implemented. Refrigerants with glide are suitable for these applications.

The use of Isceon 79 can require installation of additional refrigerating capacity. With this replacement refrigerant, the oil does not necessarily have to be replaced, provided that i) good separation at the compressor outlet is ensured and ii) good plant design prevents "oil traps".

Direct-expansion installations

(applications above 0 °C)

R407C is used in water chillers. For plants using several systems, R404A and R507 can be envisaged. Isceon 29 and 59 were developed as

ahead in the case of equipment operating on R22 is as follows:

TO CARRY ON USING R22 IN EXISTING EQUIPMENT:

This solution can only be envisaged for equipment that is approaching the end of its lifespan.

A "miracle" solution that could be used to replace R22 is very unlikely to suddenly emerge.

Starting in 2010, supplies of recycled R22 will not necessarily be available.

The deadline for the ban on the use of recycled R22 (end of 2014) could be brought forward.

This solution requires in-depth examination of the existing system.

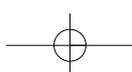
REPLACEMENT USING HFCs

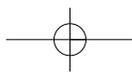
Flooded installations

(applications below 0 °C)

R404A and R507 may be suitable. However, the pressure used and the sizing of the plant and piping require careful examination.

CHARACTERISTICS OF AVAILABLE REFRIGERANTS						
Refrigerant N°+name	Composition of mixtures	At atmospheric pressure		Critical T (°C)	Critical P (bar)	GWP
		t° évapo	Glide			
R134a		-26	0	101	40,6	1300
R404A	R125/134a/143a	-46	0,8	72	37,4	3800
R507	R125/143a		0,1	0	0	3800
R407C	R32/125/134a	-44	7,2	87	46,3	1600
R410A	R32/125	-51	0,5	72,5	49,5	1900
R422D (Isceon. 29)	R125/134a/600	-44	4,8	80	39	2230
R417A (Isceon. 59)	R125/134a/600	-39	5	90	42,4	1950
R422A (Isceon. 79)	R125/134a/600a	-47	3	72	37,5	2530
R290 (propane)		-42	0	97	42,5	3
R600 (butane)						3
R600a (isobutane)		-12		135	36,4	3
R717 (ammonia)		-33,3		132	113,3	0
R744 (CO ₂)		-78		31	73,8	1
R718 (water)		100		374	221	0





COMPARISONS WITH R22

Refrigerant	Saturation pressure (bar abs.)				Range -40 °C / -10 °C		Range -10 °C / +35 °C	
	-40 °C t° rosée	-10 °C t° rosée	43 °C t° bulle	55 °C t° bulle	Refrigerating capacity	COP/COP R22	Refrigerating capacity	COP/COP R22
R22	1.05	3.55	16.49	21.75	100	1 (6.95)	100	1 (4.71)
R134a	0.51	2.01	11.01	14.91	53	0.95	62	0.98
R404A	1.32	4.33	19.64	25.83	108	0.88	99	0.86
R507	1.40	4.52	20.06	26.38	113	0.91	101	0.89
R407C	0.86	3.20	18.76	24.75	85	0.89	92	0.9
R410A	1.76	5.72	25.98	34.29	154	0.94	146	0.95
R422D (Iscéon. 29)	1	3.4	17.5		70		83	0.9
R417A (Iscéon. 59)	0.77	2.8	15.5	20.5	62		75	0.94
R422A (Iscéon. 79)	1.25	4.2	20	26.5	84	0.8	92	0.87
R717 (ammonia)	0.72	2.91	16.89	23.11	83	0.96	107	1.03
R744 (CO ₂)	10.45	26.49			696	0.9		

Values provided as an indication only / ISCEON

Refrigerant	Comments
R22	Highly polyvalent refrigerant - no single refrigerant covers R22's full range of application, but several refrigerants can be used within certain ranges
R134a	For use in applications above 0 °C given its boiling point and COP under these condition, in spite of its low volumetric efficiency
R404A	Its relatively low boiling point and its high volumetric efficiency make this refrigerant valuable in applications below 0 °C
R507	Same as R404A
R407C	Its glide makes it suitable for direct-expansion applications, particularly in applications above or just below 0 °C
R410A	This refrigerant has some useful features but its high pressure limits its use
Range of Iscéons	The Isceons are HFCs containing 3-4% HC. This component is designed for mineral oil return. This feature means that R22 can be replaced in a plant without changing the oil
R422D (Iscéon. 29)	For use in applications above 0 °C, particularly in water chillers
R417A (Iscéon. 59)	For medium temperature applications
R422A (Iscéon. 79)	For applications below 0 °C
R717 (ammoniac)	For industrial applications above and below 0 °C
R744 (CO ₂)	For applications below 0 °C. A transcritical cycle is developed

“drop-in” replacements for R22 this type of application. Advice on the use of Isceon 79 also applies to these refrigerants. When replacing R22 with an HFC, particular attention must be paid to joints.

Replacement with an ammonia system

Certain flooded industrial installations have been designed for use with ammonia as a refrigerant at a later date. In these installations, the materials used for the various components must be compatible with NH₃ (copper should not be used) and the same applies to joints. During such retro-

fitting, the installation has to be stopped for a long period in order to enable flushing to be performed.

REPLACEMENT OF A REFRIGERATION PLANT

This solution is radical and undoubtedly the most expensive in the short term. However, it is often worth considering in the context of medium- and long-term needs.

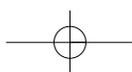
This solution makes it possible to optimize energy efficiency and to use the best available technologies at the time of replacement, with or without a secondary refrigerant.

It makes it possible to ensure that the plant complies with various regulations and standards.

The tables in the annex provide the characteristics of the refrigerants that can be used and the differences in performance with respect to R22.

CONCLUSION

- Each refrigerant has its own specific characteristics
- Before a replacement, a study must be conducted
- So far, no “miracle” or “universal” refrigerants have become available. ●





Mark Menzer

Refrigerant Use and Emission Reduction in the U.S.: 2008

MARK MENZER, XUDONG WANG

AHRI Air-Conditioning, Heating and Refrigeration Institute

In January, 2008, the Air-Conditioning and Refrigeration Institute (ARI) and the Gas Appliance Manufacturers Association (GAMA) merged to form the Air-Conditioning, Heating, and Refrigeration Institute (AHRI). AHRI is the trade association representing manufacturers of air conditioning, heating and commercial refrigeration equipment. AHRI's 350+ member companies account for more than 90 percent of the residential and commercial air conditioning, space heating, water heating, and commercial refrigeration equipment manufactured and sold in North America. AHRI's principal activities are advocacy, the development of product standards, the administration of product performance certification programs and research.

The HVACR market in the U.S. is unique. Traditional building practices and the style of living both lead to appliances and heating and cooling equipment that are sometimes different than the rest of the world. For example, Americans tend to shop for groceries only one or two times a week and store them for longer periods, thus necessitating larger refrigerators. The refrigerant charge (averaging around 0.3 kg) and amount of foam used for insulation is also greater than in most other parts of the

world. Refrigerant 134a is used exclusively for the household refrigerators. Most homes in the U.S. employ central comfort conditioning systems, generally both heating and cooling. U.S. Government data shows that two-thirds of all homes in the United States have central air conditioners and that about 90% of single family and multi-family buildings built after 2004 have air-conditioning [1]. Residential air conditioners use about 5% of all the electricity produced in the United States [2]. For homes and buildings where central air conditioners were not originally or cannot be feasibly installed, room or window air conditioners are commonly employed. Ductless systems, also called mini-split air conditioners, common in most of the world, have been less common in the U.S. although a bit moreso in recent years.

The common application is as retrofit add-ons to houses with "non-ducted" heating systems, such as hydronic (hot water heat) heating systems [2]. In U.S., a majority of homes are heated by either furnaces or boilers. Split system reversible heat pumps with/without supplementary heating devices are also common. Around 29% of single family homes and 35% of units in multi-family buildings built during past five years have heat pump systems [1]. These systems have typically used HCFC-22 and new systems are transitioning to HFC-410A, but only about one-third of current shipments contain 410A.

In commercial buildings, a variety of

heating and cooling systems are employed. There are many arrangements of air-to-air systems, including rooftop unitary, package terminal equipment, and single package vertical units. All have used HCFC-22. Water source heat pumps have increased in popularity as have small chillers. In larger buildings, chillers predominate. High-pressure chillers use HCFC-22 and HFC-134a, and low-pressure chillers use HCFC-123. The breakdown of the energy use of commercial cooling equipment is illustrated in Figure 1. Packaged air-conditioning units (mostly rooftop units) consume more than half of the total energy in the commercial cooling sector. Chillers use 31% of total energy in commercial cooling sector.

Overall, U.S. residential and commercial air-conditioning have greatly relied on HCFC-22. However, under the Clean Air Act, the production and import of newly manufactured equipment utilizing HCFC-22 will stop in the United States by January 1, 2010. The production and import of HCFC-22 will be banned entirely in the United States by January 1, 2020. Once this happens, only recycled/reclaimed or stockpiled quantities of HCFC-22 will be available for servicing existing equipment [3]. At that time, the availability of HCFC-22 is expected to decrease, and the price is expected to increase as will the cost of service and maintenance for old systems using HCFC-22. Table 1 shows a list of the most common types of refrigerants used for different equipment types and

planned replacement refrigerants, in which it indicates that most equipment is being or will be altered to HFC-134a, R-410A, or R-407C [7].

ALTERNATIVE REFRIGERANTS AND SYSTEMS

In the U.S., researchers from academic and industrial sectors are making great efforts to find and implement alternative low GWP refrigerants to the HVACR fields.

Refrigerant manufacturers, DuPont and Honeywell, are working closely with automotive OEMs on the development and commercialization of a low global warming potential (GWP) refrigerant, hydrofluoro-olefin (HFO)-1234yf. HFO-1234yf has only a 100 year GWP of 4 and has zero ozone depletion potential. Studies on its toxicity, flammability, materials compatibility, system performance and life cycle climate performance show potential to be implemented in automotive and stationary HVACR applications, pending completion of risk assessments [4].

Performance tests have been conducted for automotive applications, but have yet to begun for stationary equipment. Traditionally, hydrocarbons, ammonia and carbon dioxide are well-known low GWP refrigerants. Ammonia is used in the U.S. for many low temperature refrigeration applications. A major barrier of using these low GWP refrigerants in U.S. is safety or system efficiency. The hydrocarbon refrigerants are flammable; carbon dioxide can be potentially lethal when the concentration is high and it also exhibits low cycle efficiency, especially when the condensing temperature is near its critical temperature.

Secondary loop systems may be a promising option to solve these problems. Studies on how to safely use these refrigerants and improve system efficiency are underway.

ACTIVITIES TO MINIMIZE EMISSIONS

Although the United States is not a signee to Kyoto Accord on Climate Change, the U.S. is committed to reducing the greenhouse gas intensity

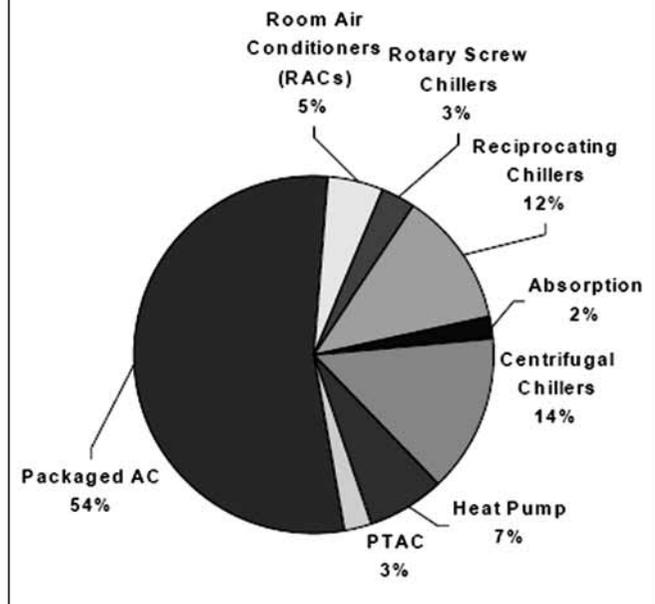
of the American economy by 18 percent over the 10-year period from 2002 to 2012 [3]. Efforts have been made to reduce both direct and indirect emissions. Many regulations, voluntary initiatives and incentive-based programs will help the U.S. achieve this goal.

Regulations

Since, for most HVACR applications, indirect emissions (from the power plant) greatly exceed direct emissions, higher efficiency systems can lead to much lower green house gases (GHG) emissions.

For many years, HVAC equipment in the U.S. has been subject to standards for minimum efficiency. Most of the efficiencies are set by the Federal government or by American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) through their Standard 90.1. The energy efficiency of the residential central air-conditioners has improved significantly. Figure 2 shows the shipment-weighted average SEER of the units from 1970 to 2006. It has increased 45% since the enactment of the National Appliance Energy Conservation Act (NAECA) in 1987 [8]. The current minimum standards in residential sector are 13 SEER for split system and single package air conditioners, and 13 SEER, 7.7 HSPF

Figure 1:
Primary energy use breakdown of commercial cooling equipment (Total 1.4 Quads) [7]



for split system and single package heat pumps which took effect in January 2006. In December 2007, President Bush signed the Energy Independence and Security Act of 2007, which gives U.S. Department of Energy (DOE) the authority to establish regional standards (up to three U.S. regions for cooling and two regions for heating) for residential furnaces and central air conditioning equipment. The standards may set minimum efficiency levels based on different regional climates.

In an effort to reduce refrigerant emissions, the U.S. Environmental Protection Agency (EPA) has mandated the repair or replacement of equipment that have emissions over the maxi-

Table 1:
Current and future refrigerants [7]

Equipment Type	Traditional Refrigerant	Replacement Refrigerants
Rotary Screw- Chiller	HCFC-22	R407C, HFC-134a
Scroll Chiller	HCFC-22	R407C, R-410A
Reciprocating Chiller	HCFC-22	R-407C, R-410A
Absorption Chiller	R-718 (water)	R-718
Centrifugal Chiller	CFC-11, CFC-12	HFC-134a, HCFC-123
Packaged Air Conditioners	HCFC-22	R-407C, R-410A
Heat Pump	HCFC-22	R407C, R-410A
PTAC, PTHP	HCFC-22	R-407C, R-410A
Room Air Conditioning	HCFC-22	R-407C, R-410A

mum allowable. In addition, they have established rules for the recovery and reuse of refrigerants.

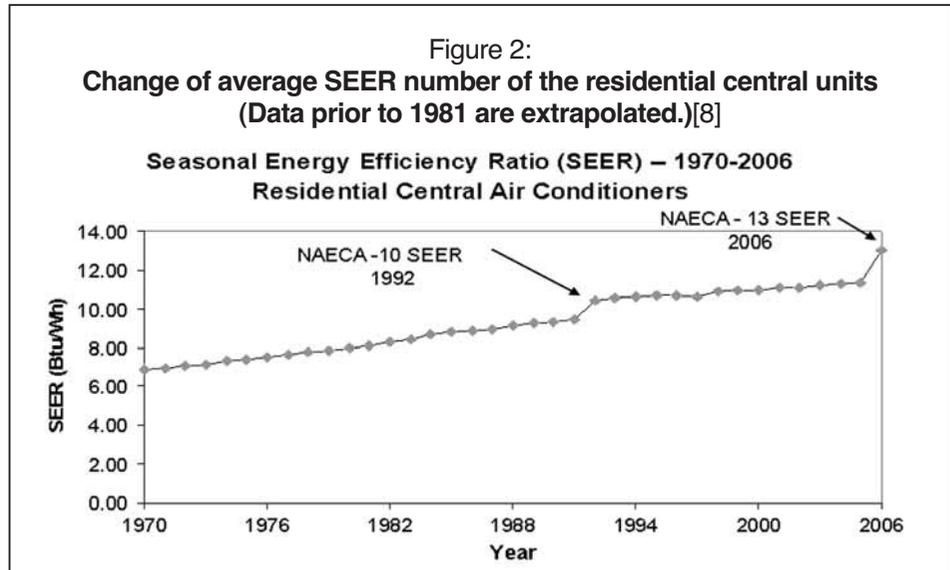
Initiatives

In HVAC&R sector, voluntary initiatives include Clean Energy-Environment State Partnership, Climate Leaders Program, Combined Heat and Power (CHP) Partnership, ENERGY STAR Program, Green Power Partnership, High GWP Gas Voluntary Programs and Voluntary Greenhouse Gas Reporting Program launched by EPA and DOE. The federal government also proposed \$3.6 billion energy tax incentives budget over 5 years starting from 2006 to promote the use of cleaner, renewable energy and more energy-efficient technologies that reduce greenhouse gas emissions [3].

EPA and DOE launched Energy Star Building program to promote high energy efficiency buildings. Energy star labeled homes are at least 15% more energy efficient than homes built to the 2004 International Residential Code (IRC), and include additional energy-saving features that typically make them 20-30% more efficient than standard homes [5]. Meanwhile, the LEED rating system of the U.S. Green Building Council is designed to promote sustainable buildings. Points are given to buildings that use high efficiency, low ODP/ low GWP refrigerants and/or low leakage systems. There were about 1,737 certified LEED projects worldwide as of August, 2008, of these 1536 were in the U.S. [6].

As noted above, minimum energy efficiency regulations and these initiatives will effectively reduce the impact of indirect greenhouse gas emissions which is associated with the emissions (primarily carbon dioxide) from the generation of power required to operate the equipment. In HVAC&R sector, the indirect emissions may outweigh the direct emissions that occur in system failure, leaks and purge during operation, or in servicing and disposing processes.

Good technician practice is essential to reduce the direct refrigerants emissions through the servicing process. In U.S., technicians must be certified by passing a test demonstrating the skill of properly handling refrigerants and the knowledge of EPA refrigerant regulations in order to repair or service equipment [3].



EPA has launched Responsible Appliance Disposal Program (RAD). The RAD partners ensure that refrigerants from old refrigerators, air-conditioners are recovered and reclaimed or destroyed [3]. GreenChill Advanced Refrigeration Partnership is another initiative that EPA cooperates with the supermarket industry and other stakeholders to promote advanced technologies, strategies, and practices that reduce refrigerant charges and emissions [3].

FUTURE ACTIVITIES

Several proposals for addressing the emission of global warming gasses have been introduced in the U.S. Congress, but no action has been taken as of this writing. It is expected that some form of cap and trade program for global warming gasses will be introduced and may be enacted. In addition, the Air-Conditioning, Heating, and Refrigeration Institute has proposed a program, called Refrigerant Management USA, to provide incentives to contractors who return used refrigerants for reclaiming or for destruction. The funds for these incentives would come from a producer levy on new refrigerants manufactured or imported to the U.S.

Industry is working through ASHRAE to revise ASHRAE Standard 147, Reducing Release of Halogenated Refrigerants from Refrigeration and Air-Conditioning Equipment and Systems. The new standard is expected to specify

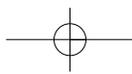
that equipment containing refrigerants should be leak tested. Manufacturers are designing equipment that have a lower volume of refrigerants and that are more leak-free. The use of secondary coolant systems, particularly in supermarkets, will lower the amount of refrigerant emissions.

CONCLUSION

Vapor compression HVACR systems are pervasive in the U.S. Many of these systems rely on HCFC-22 or other HCFCs which are being phased out. In addition to refrigerants with zero ozone depletion, manufacturers are evaluating other alternatives, including low-GWP refrigerants. Recognizing the importance of minimizing both direct and indirect emissions of global warming gases, the U.S. has instituted a number of regulations, standards and incentive programs to achieve this.

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Development Trends of Ammonia Refrigeration Technology

YANG YIFAN and HU WANGYANG

Chinese Association of Refrigeration

Chinese Association of Refrigeration (CAR) was founded on April 25th, 1977. CAR is a national scientific organization in the field of refrigeration and air-conditioning industry and trade, which is subordinated to China Association for Science and Technology (CAST). CAR formally joined in the International Institute of Refrigeration (IIR) in January 1978, and became a second grade membership country. CAR always aims at solidifying and serving its members and technical personnel, and developing the science and technology of China refrigeration. In response to the global needs of protecting the ozone layer and reducing the greenhouse effect, CFC refrigerants are being phased out because they destroy the atmosphere and cause the greenhouse effect, and the use of HCFC refrigerants is being gradually limited. This paper analyzes the properties and application history of ammonia, an environmentally-friendly refrigerant (ODP=0, GWP=0), and predicts the development trends and future problems of ammonia refrigeration technology based on ammonia refrigeration system optimization, control technology, safety, system miniaturization, etc.
Keywords: Refrigerant, ammonia refrigeration system, safety, development trends.

INTRODUCTION

Ammonia is a common, cheap inorganic compound and is also a natural refrigerant (R717). Due to its good thermodynamic properties and the fact that it does not harm the atmosphere, it plays an important role in the development of refrigeration technologies. At present, ammonia is not able to be used in household or air-conditioning systems because of its toxicity and explosion potential at certain air concentrations, but is mainly used in large-scale industrial refrigeration and commercial frozen storage.

In recent years, everyone has recognized the international consensus of the CFC phase-out and reduction of HCFCs based on the fact that fluorocarbon refrigerants destroy the ozone layer and generate the greenhouse effect. Today we are trying to find new refrigerants which are not harmful to the ozone layer and do not contribute to the greenhouse effect, and we are putting more attention on natural refrigerants. Technicians have already begun exerting their efforts reevaluating and researching ammonia safety, systems and equipment.

Some ammonia equipment with key technology and control units have been developed and put into mass production, which creates favorable conditions for the promotion of ammonia refrigeration technology. How to speed up the research and application of ammonia systems is becoming a key subject of refrigeration shareholders all over the world.

As an environmentally-friendly refrigerant, ammonia is becoming popular in China, but will not completely replace CFC and HCFC refrigerants in recent years

MAIN CHARACTERISTICS

Excellent environmental and thermodynamic properties

Ammonia is a natural medium-temperature refrigerant with excellent environmental and thermodynamic properties: 1) ODP=0, GWP=0, an environmentally-friendly refrigerant.

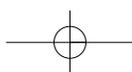
2) Critical temperature is 132.3°C, critical pressure is 11.33MPa, higher than that of R22 (96.2 °C/4.99MPa) and R410A (70.2 °C/4.79MPa)^[1]. Standard boiling temperature is low (-33.4 °C), large volumetric refrigerating capacity, high conductivity coefficient, high evaporative latent heat (6.4 times that of R22, 5.5 times that of R410A at -15 °C), low throttling loss, high refrigeration coefficient, smaller size of compressors and heat exchangers compared with that of R22 at the same temperature and refrigerating capacity.

3) Molecular weight is 17, vapor density is lower than that of air, it easily rises and escapes from the roof when leakage occurs, easily dissolves in water during a large leakage.

4) Easily purchased at a low price, the charge cost is about 1/10 that of R22 for the same volume.

Disadvantages

Ammonia was replaced by fluorocarbons to some extent for a period of



time because it is not a perfect refrigerant, and has the following disadvantages:

1) High adiabatic coefficient ($k=1.40$), high compressor discharge temperature at low evaporating temperature and high condensing temperature. Cooling must be used in order to ensure the function of the lubricating oils.

2) Does not corrode metals like steel and aluminum, but corrodes zinc, copper, and copper alloys (except phosphor bronze) when containing moisture.

3) Ammonia has a pungent odor with toxicity and flammability^[2], and causes damage to humans exposed to it when the concentration reaches the limit, and causes an explosion with flame when the concentration of ammonia in air reaches 16÷25% at high temperature^[3], but belongs to the lowest explosive danger class. The application of ammonia is banned in some areas for the above disadvantages, especially in air-conditioning systems of civilian buildings.

Today, natural refrigerants are becoming more and more popular. Many experts think the above disadvantages were always exaggerated during the era of fluorocarbons^[4]. In fact, ammonia's ignition point is 700÷780°C, therefore it is not easy to burn without a flame providing enough heat. (In the Japanese earthquakes of Niigata and Sendai, much refrigeration equipment was destroyed, but there were no reports of explosion and fire.) Ammonia's limit of inflammability is 3~7 times higher than that of hydrocarbons and natural gases, but the combustion heat is 50% compared to them, and the toxicity is 1/10÷1/50 that of chlorine^[5]. We should recognize the property of ammonia's pungent odor from two aspects: one is that the pungent odor stimulates noses and throats, makes humans feel uncomfortable, and the other is that the pungent odor makes humans conscious of even a tiny leakage. Thus a small leakage can be found immediately even when the concentration is far below the explosive concentration. Moreover, ammonia vapor is lighter than air, can easily be discharged to the outside through ventilation, and is absorbed quickly when meeting water. All these properties



The last International Congress of Refrigeration was organized by the IIR and the CAR in Beijing (China) in August 2007.

make ammonia easily removed from air to reduce accidents. One hundred years of application indicates that ammonia has a low accident rate.^[6] For example, there were only 168 accidents in Japanese ammonia systems for 25 years during 1967~1991 according to the statistics of the Japanese Fluorocarbon Countermeasure Committee. Forty-eight of them (29%) were due to corrosion of lines and seals, 52 (32%) were daily operation mistakes (such as liquid seal installation, defrosting operation, shutoff valve operation, refrigerant charging and reclaiming, oil discharging etc.), 13 (8%) were broken gauges, 22 (13%) were maintenance mistakes, 31 (18%) were the rest. All the accidents caused 9 deaths, 2 badly injured and 127 slightly injured.

PRESENT STATUS

Refrigeration systems

Most ammonia systems used in food freezing and storage are direct systems, only a few are indirect systems to address safety issues. In order to avoid leakage in the storage room and reduce the system charge of ammonia, indirect systems are used with ammonia as refrigerant, and glycol as a coolant in large-scale cold storages for vegetables and fruits. Recently, NH_3/CO_2 cascade systems have begun to be used in Europe and the USA by using NH_3 in the high-temperature stage and CO_2 in the low-temperature stage^[7], thus avoiding the risk of a leakage damaging the food safety and quality in accidental conditions like earthquakes, and reduce the

system ammonia charge to improve the system safety.

Since the 1970s, gravity supply liquid and liquid pumps have been commonly used^[8]. After the 1980s, with the development of computer microelectronics, fully-automatic or self-automatic ammonia systems using liquid pumps were developed with PLC and DCS systems. In 2000, DANFOSS electric expansion valves were first used to control direct expansion in ammonia systems for aquatic food products in Dalian, China; thus the systems were greatly simplified.

Indirect ammonia systems are usually used in chemical industries, large air-conditioning systems, brew houses and pharmaceutical factories, such as the two-stage ammonia absorption system powered by waste heat in Nanjing, China built in 1988, which can also run at the two evaporating temperatures of -20°C and -30°C^[4].

Components

At present, piston and screw compressors are commonly used in ammonia refrigeration systems. Prior to the 1980s, shell and tube heat exchangers were common, but were replaced by plate heat exchangers for its disadvantages of high weight, big size and low efficiency. Plate heat exchangers had a history of 20 years in fluorocarbon systems, but they were not used in ammonia systems because the welding material contains copper. When CFCs were phased out and HCFCs were reduced, plate heat exchangers were reused in ammonia systems with some improvements to conventional ones.

Lubricating oil

Lubricating oil has the function of lubricating, cooling and sealing the surfaces between moving components, and can ensure the safety, reliability and life of compressors. Mineral oil is very common and has good performance, but it is not compatible with ammonia, so an oil separator and an oil collector are essential parts of ammonia systems. The oil system is very complex and hard to self-control. In order to simplify oil systems or use a dry-type evaporator, oil must be compatible with ammonia, such as PAG oil.

DEVELOPMENT TRENDS

Ammonia has a history of more than 100 years in refrigeration systems, so its advantages and disadvantages are fully understood. As a natural refrigerant, ammonia has obvious advantages in replacing CFCs and improving continuous development, saving energy and environmental protection. The most important issue is how to use ammonia safely.

Low charge

The charge of ammonia depends on the refrigerating cycle, but ammonia systems have many containers and lines, and are more complicated than fluorocarbon systems. The charge is comparatively larger for the same refrigerating capacity. In order to reduce the charge, new ways shall be found from two aspects: a) simplify the systems, and b) increase heat transfer efficiency. Decreasing the charge means increasing the system safety.

System simplification

The invention of oil compatible with ammonia provides the basis for system simplification, and designers can use the principles of fluorocarbon systems to design ammonia systems. The system safety can be greatly improved by system simplification.

Heat exchanger volume reduction

The heat transfer efficiency is increased and the inner volume decreased by using high efficiency plate heat exchangers, and the reduction of ammonia liquid insures the security of the system. The quality of ammonia equipment is ensured and



As an environmentally-friendly refrigerant, ammonia is becoming popular in China, but will not completely replace CFC and HCFC refrigerants in recent years

the COP is continuously increased with the development of enhanced heat transfer, metal materials, lubricating oils, efficient compressors and manufacturing technologies.

Packaged and compact

Compact commercial ammonia systems were very popular during 1930-1940, but there has been no substantial improvement until now and the old original systems can't be accepted in today's market. In order to widely use the systems, we need to enhance the heat transfer, reduce the size, develop new electrical expansion valves and smaller hermetically-sealed compressors, and make the equipment packaged and compact through system simplification and optimization.

Automatic control

Twenty-first century control technology, computer networks, and long-distance monitoring provide technical support for automatic system control, and also create the development space for fully automatic control. Automation involves issues of oil, electric expansion valves, system design, and system static and dynamic characteristics. The settlement of the above issues will accelerate the automatic process and bring new changes for efficient operation, safe applications, protection and cost reduction.

Better safety and reliability

Safety is the central premise of ammonia technology because of ammonia's toxic and explosive properties at cer-

tain conditions. System safety and eliminating leakage are crucial to ammonia refrigeration systems.

In order to reduce leakage, research institutes and manufacturers are bound to develop new hermetically-sealed compressors in addition to the technical improvements on conventional open-type compressors. System accidents can easily be handled because ammonia is a natural refrigerant, soluble in water, and ammonia-water can be used as fertilizer. With the perfect safety measures, rigorous rules for application, correct operation and maintenance, and specialized training of system operators, ammonia refrigeration systems will ultimately have a better future.

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Francesco Asdrubali

Solar cooling with small-size absorption chillers: different solutions for summer air conditioning

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The research group of Applied Physics, Department of Industrial Engineering of the University of Perugia, is active in all the fields of Environmental and Industrial Applied Physics. Even though it is difficult to classify all the activities, the main fields of research are applied thermodynamics, heat transfer, energy systems and environmental impact, applied acoustics, lighting technique. The experimental facilities include three laboratories: thermodynamics, environmental control, acoustics and vibrations, equipped with up to date instruments and simulation tools. As far as applied thermodynamics, the research activity deals, above all, with non conventional refrigerating machines focusing mainly on absorption refrigeration. In this field, thermophysical properties of new refrigerating fluids are measured and calculation codes are formulated for the simulation of the various types of machines functioning. An experimental plant has been set up for measuring a Lithium Water-Bromide refrigerating unit supplied by solar energy. Other research fields include water evaporation from open basins and production of hydrogen with unconventional systems.

Absorption refrigerating machines represent an interesting alternative to compression machines, especially when waste heat or heat produced by solar energy is available; the market is beginning to propose small-size absorption machines especially designed for air conditioning in residential buildings. A survey of small-size absorption refrigerators is presented, with particular emphasis on their performance when the heat source comes from solar energy. The machines examined cover a range of chilling powers (4 to 15 kW) and have different working principles. The study is conducted using data supplied by manufacturers and collected in an experimental set-up realized by the University of Perugia; different refrigerators are compared taking into account the most significant parameters, such as heat source and chilled water temperature, cooling circuit characteristics, coefficient of performance, dimensions and weight.

INTRODUCTION

The summer air conditioning demand is growing continuously, not only in the tertiary sector but also in residential applications; the corresponding demand for electric power may cause failures in the electricity supply network, which must cover increasingly higher peak loads. Heat assisted cooling systems represent a fascinating solution, especially when waste heat or heat produced by solar energy is available, also considering that they do not use CFCs, but solutions with

low environmental impact; therefore, they could represent one solution to the energy-environmental issues linked to international agreements, such as the Kyoto Protocol for CO₂ emissions reduction, or the United Nations Framework Convention on Climate Change (FCCC) and the Montreal Protocol, whose aim is to abandon the use of CFCs in cooling cycles. The most common techniques that nowadays permit cold production starting from heat could be grouped into two categories: desiccant cooling systems, which produce directly cooled air with an open cycle, and thermally driven chillers, which deliver cooled water[1]. In the latter case, absorption machines represent the most common solution in actual installations, though adsorption chillers are becoming more and more interesting. As a matter of fact, adsorption machines guarantee higher efficiency at low driving temperatures, but they should be considered still at the research level. Absorption chillers can work with a single or double stage cycle, the latter being more efficient but at the same time employing a hot fluid temperature between 140 °C and 160 °C. These considerations focus the market's attention basically on small-size absorption machines, especially designed for air conditioning in residential buildings, employing low temperature heat [2 and 3]. This work is aimed at giving a survey of these available solutions, with particular emphasis on variations in their performance depending on external conditions.

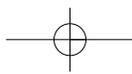
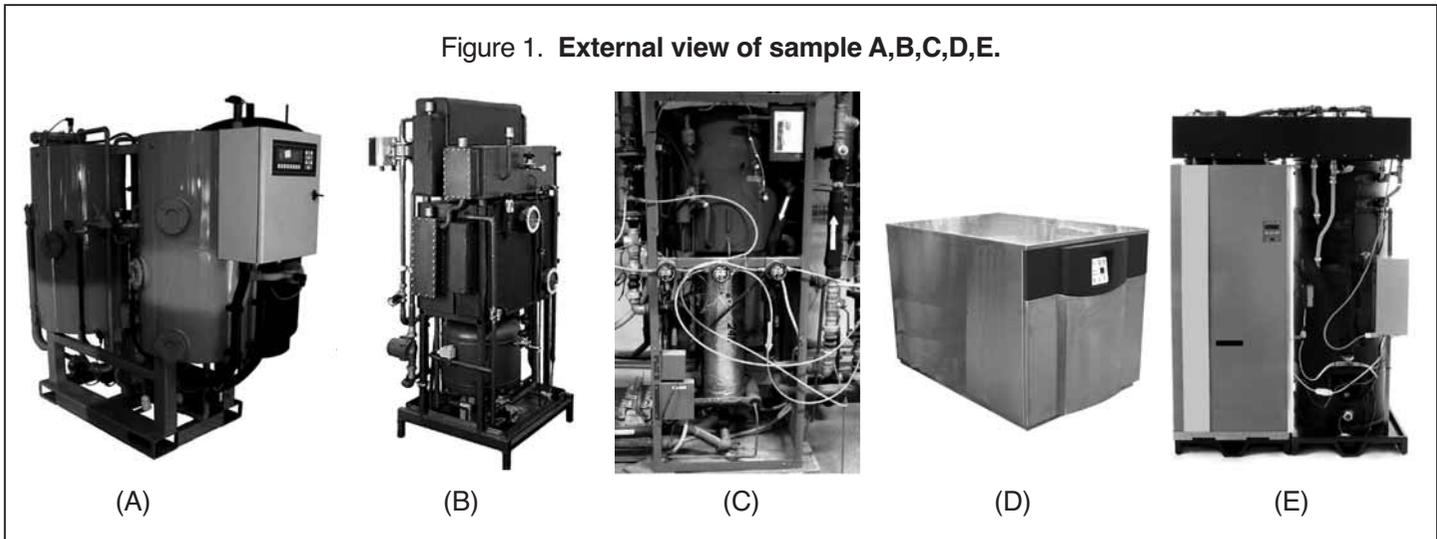


Figure 1. External view of sample A,B,C,D,E.



DRIVING ABSORPTION MACHINES WITH SOLAR ENERGY

At present, the huge potential of the residential building cooling market is almost completely covered by electric chillers, heat pumps and (with less success) gas-fired absorbers. The main problems linked to solar-driven absorption machines are a strict plant dependence on environmental parameters (such as external air temperature, solar irradiation level and wind speed), a high initial cost and the efficiency of solar contribution limited to the central hours of the day.

The plant has to be connected to an evaporative cooling tower removing the heat released by the condenser and by the absorber of the chiller. Besides, an intrinsic characteristic of the plant limits its overall performance: although absorption cycles reach highest efficiencies when heat sources are available at a high thermal level, solar panels behave in the exact opposite manner: both flat and evacuated-tube collectors have efficiencies that decrease with the rising of the circulating fluid temperature.

Lastly, even though the cooling load and the solar irradiation take place more or less at the same time of day, there can be many occasions when the ideal match between the sun and the absorption machine does not occur: hot days with little irradiation, morning or late evening cooling loads and sunny days without cooling demand.

Control strategies must tend towards reaching the highest efficiency, combining flexibility, inexpensiveness and

ease of installation. Two main control modes can be adopted: the solar-guided mode and the cold-guided mode. With the first approach, solar collectors are linked directly (or by an external heat exchanger) to the generator of the absorption machine; this solution makes it possible to transfer all of the energy gathered by the collectors straight to the machine, without passing through a storage tank. Choosing this alternative, although the generator is fed with high level thermal energy, the control possibilities remain greatly limited; therefore, each variation of the solar input is transmitted to the chilled water and then to the user. Besides, in case of low irradiation, there is a transient effect characterized by continuous ON-OFFs, resulting in a decrease in efficiency and unwanted intermittent absorption cycle behavior. The plant does not follow building cooling loads, so its applications are limited to users without steady cooling requirements. In the case of cold-guided mode control, the whole system has to guarantee a defined cooled water temperature or a fixed cooling load; therefore it is necessary to put a hot storage tank between the collectors and the absorption machine, thus allowing a minimum of control, storing the energy when the production exceeds the cooling load and also feeding the generator at the desired temperature when the solar radiation is not sufficient.

With this solution a series of heat losses is introduced: the dispersion through the tank surface, the energy wasted in the heat exchanger between the solar circuit and the hot storage, and the

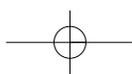
coils between the generator feeding circuit and the hot storage. There is also the possibility of installing a cold storage, with the effect of giving a higher inertia to the load, avoiding the intermittent functioning of the absorption machine.

INVESTIGATED SMALL-SIZE ABSORPTION CHILLERS

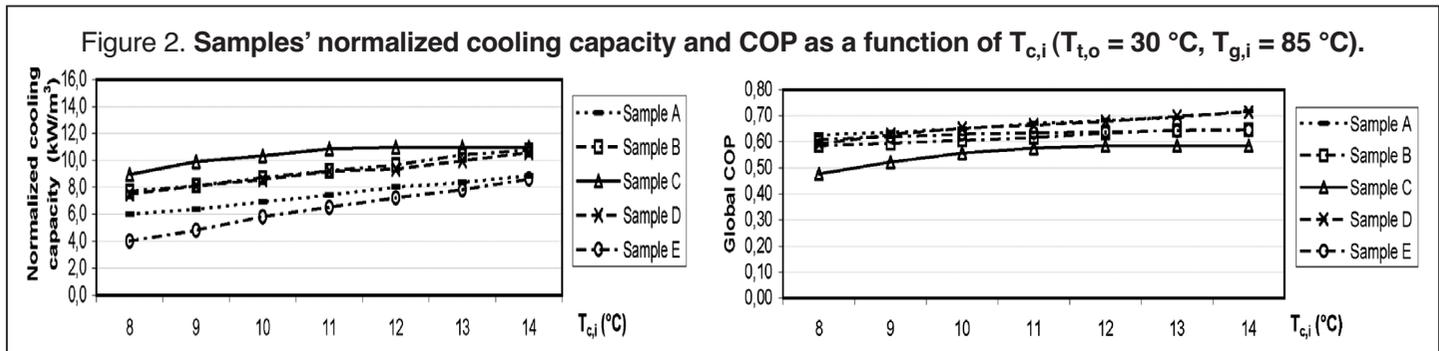
The market for small-size absorption chillers seems to be barely developed, probably because of the cutthroat competition of electric chillers and heat pumps; nevertheless, it was possible to find and analyze five absorption machines, built by different manufacturers, even though most of them should be considered more as prototypes rather than as commercially available items.

Machine A

The first sample is made up of two separate steel units in which the evaporator-absorber and generator-condenser pairs are placed respectively (Fig. 1,A). The refrigerant-absorbent pair is Water/Lithium Bromide, evolving inside a classic single stage absorption cycle with a regenerator (plate heat exchanger) between the absorber and the generator. Two electric pumps provide circulation between the absorber and the generator, and the periodic suction of incondensable gases is done by a built-in vacuum pump. The cooling capacity under fixed conditions (see paragraph 4) is approximately 11 kW, and the heat extraction is carried out under all conditions by a 35 kW evapo-



Position	Parameter	M.U.	Sample A	Sample B	Sample C	Sample D	Sample E	Sample F
Cooling circuit	Capacity	kW	11.4	8.4	9.3	5.2	4.8	10.0
	$T_{c,o}$	$^{\circ}\text{C}$	9.0	9.0	9.0	9.0	9.0	16.0
Heating circuit	Power	kW	16.6	13.0	16.0	7.6	7.1	15.6
	$T_{g,i}$	$^{\circ}\text{C}$	85.0	85.0	85.0	85.0	85.0	75.0
Re-cooling circuit	Power	kW	28.0	21.4	25.3	12.8	11.9	25.6
	$T_{t,o}$	$^{\circ}\text{C}$	30.0	30.0	30.0	30.0	30.0	24.0
Electric absorption		kW	1.4	1.1	1.8	0.7	0.7	1.3
Global COP		-	0.64	0.59	0.52	0.63	0.62	0.59
Weight		kg	700	350	325	240	740	350
Overall dimensions	Length	mm	1500	855	750	1130	700	800
	Width	mm	750	653	716	720	680	600
	Height	mm	1600	1847	1750	790	1850	2200
Volume		m^3	1.800	1.031	0.939	0.643	0.881	1.056
Norm. cooling capacity		kW/m^3	6.4	8.1	9.9	8.1	4.8	9.5



rative cooling tower [4].

Machine B

The second absorption machine examined was found to be similar in construction to the previous one: it follows the normal Water/Lithium Bromide single stage absorption cycle, with only one electric solution pump to overcome the pressure difference between the absorber and the generator, divided by the heat regenerator (Fig. 1,B). According to the manufacturer, the machine could work with a wide range of generator temperatures (from 55°C to 105°C); the cooling capacity under fixed conditions is about 10 kW, and a 25 kW evaporative cooling tower is necessary[5].

Machine C

The main characteristic that distinguishes this machine from the others is the absence of the solution pump: the circulation from the absorber to the generator is carried out by a bubble pump that does not need electricity.

The machine operates with a single stage Water/Lithium Bromide absorption cycle using a plate heat exchanger as a regenerator; the fixed-conditions cooling capacity of 15 kW requires coupling with a 45 kW evaporative cooling tower. This model was tested at the University of Perugia labs, with the installation of a solar field, measurement equipment and a data acquisition system (Fig. 1,C), with the aim of evaluating the influence of external circuits to the overall functioning of the solar cooling plant. Experimental data obtained in the test rig at the University of Perugia (solar-driven machine) can be found in [6]; for this study, however, only data provided by the manufacturer were used.

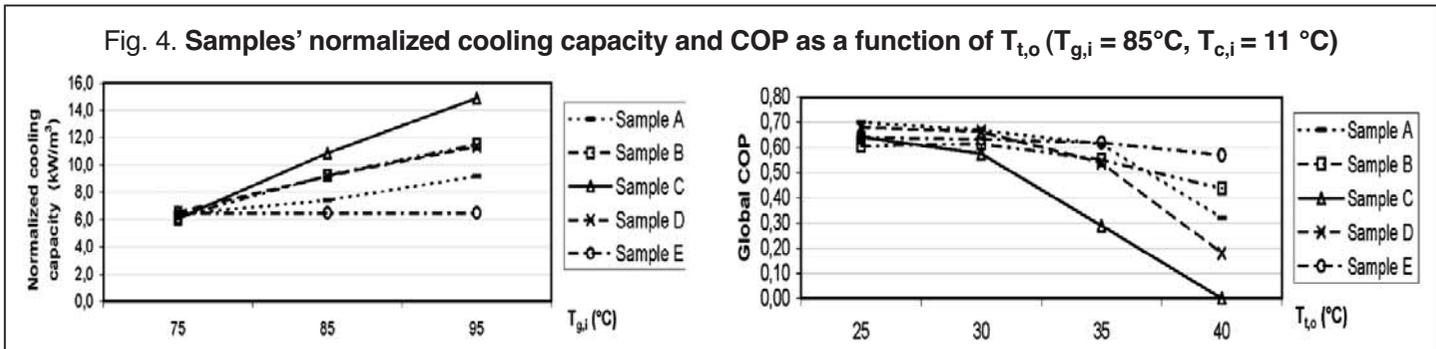
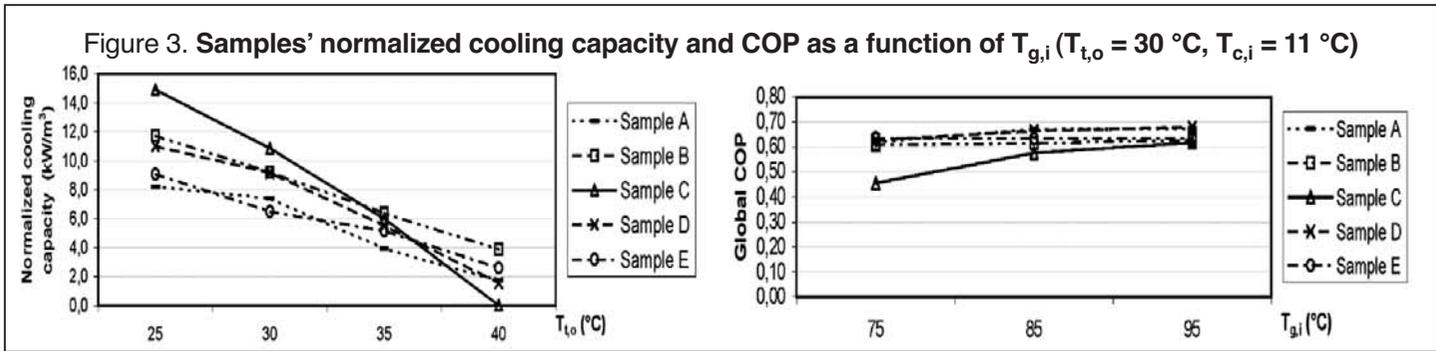
Machine D

The fourth sample is distinctive in that it has a rotating generator: the chamber that hosts the generator rotates at a speed of about 4.3 rps; according to the manufacturer, this characteristic

enhances the heat and mass transfer process inside the generator itself, permitting a consistent size reduction. The rest of the cycle reflects the normal Water/Lithium Bromide single stage absorption cycle, with a difference in the dissipation device, which is a wet-type built into the machine (Fig. 1,D). The nominal cooling capacity is about 5 kW [7].

Machine E

The last sample (Fig. 1,E) uses triple-state absorption technology with a Water/Lithium Chloride solution; this makes it significantly different from the traditional absorption processes, since it is a three-phase process (solid, solution and vapour). It works intermittently with two parallel accumulators (barrels), each comprised of a reactor and a condenser-evaporator: in the charging period, the input heat is converted into chemical energy by drying the salt (LiCl); afterwards, the cooling effect is obtained by inverting the cycle. Both



sequences need a heat sink, which could consist of a standard dissipation device such as an evaporative cooling tower. The nominal cooling capacity is about 4 kW.

Other

Researchers and companies have developed other prototypes of small-size absorption machines; for example, a single effect ammonia/water absorption chiller equipped with a membrane solution pump is under development [9], providing nominal cooling capacities between 5 and 20 kW. This solution, as well as others not mentioned, lack complete experimental data, therefore they were not included in this investigation, except for a performance evaluation reported in Table 1, where the abovementioned chiller (sample F) is compared with the other five samples, in nominal conditions.

COMPARATIVE ANALYSIS

A comparison was made between the five different absorption machines starting from the manufacturers' rating and functioning curves. Performances were evaluated in terms of cooling capacity and global coefficient of performance (the ratio between cooling capacity and the sum of the heat given to the generator plus the electric energy absorbed). The machine compo-

nents requiring electric energy are the generator-absorber pumps (when applicable), the pumps for the circulating fluids in the evaporative cooling tower and the solar circuit and the evaporative cooling tower engine; in addition, for sample D, energy is needed for the generator rotation.

The energy consumption of the external circuits pumps was considered equal to 20 W/kW of fluids transported in nominal conditions (considering a direct connection between solar collectors and absorption machine, without cold storage) plus 10 W/kW processed by the evaporative cooling tower engine; these values were considered the same for each absorption machine analyzed, so that they did not influence relative performances.

Table 1 summarizes the results for a common nominal condition (except for sample F); taking into account that the devices are driven by solar collectors; the values were set as follows:

- generator inlet temperature $T_{g,i} = 85\text{ }^{\circ}\text{C}$;
 - machine outlet cooling fluid temperature $T_{c,o} = 9\text{ }^{\circ}\text{C}$;
 - evaporative cooling tower outlet re-cooling fluid temperature $T_{t,o} = 30\text{ }^{\circ}\text{C}$.
- The table also gives overall dimensions and the weight of each absorption machine, together with the unitary cooling capacity as the ratio between the nominal cooling capacity and the

volume of the parallelepiped circumscribed about the machine. The volume was chosen as the normalization parameter, taking into account that the small-size absorption machine target consists mainly of residential applications, where space saving could represent an important feature.

A more in-depth comparative investigation was conducted varying the three external inlet temperatures and consequently evaluating the COP and the normalized cooling capacity. When data are not directly available, the following hypothesis was assumed: if the variation of the cooling capacity with the chilled water temperature is known, at a fixed re-cooling water temperature, the trend of the cooling capacity at another re-cooling water temperature is obtained simply by scaling the previous trend. The scaling factor was derived from the cooling capacity trend vs. the re-cooling water temperature at a fixed cooling water temperature. In Fig. 2 the normalized cooling capacity and the global COP are sketched respectively as a function of the cooling circuit outlet temperature, setting the generator inlet temperature at 85 °C and the evaporative cooling tower outlet re-cooling fluid temperature at 30 °C. The first couple of graphs shows how sample C proves to be the most powerful

machine varying $T_{c,i}$ but, at the same time, it suffers in terms of performance; sample E shows the lowest normalized cooling capacity; the global COP of samples A, B, D and E are very close to each other, showing weak variations with the cooling circuit outlet temperature.

In Fig. 3 the normalized cooling capacity and the global COP are sketched respectively as a function of the generator inlet temperature, setting the cooling circuit outlet temperature at 11 °C and the evaporative cooling tower outlet re-cooling fluid temperature at 30 °C. The same considerations for sample C can be repeated for the $T_{g,i}$ variation; the normalized cooling capacity of samples B and D seem higher than the remaining two chillers, while sample E confirms its weakest performance; the global COP shows to be scarcely influenced by the generator inlet temperature.

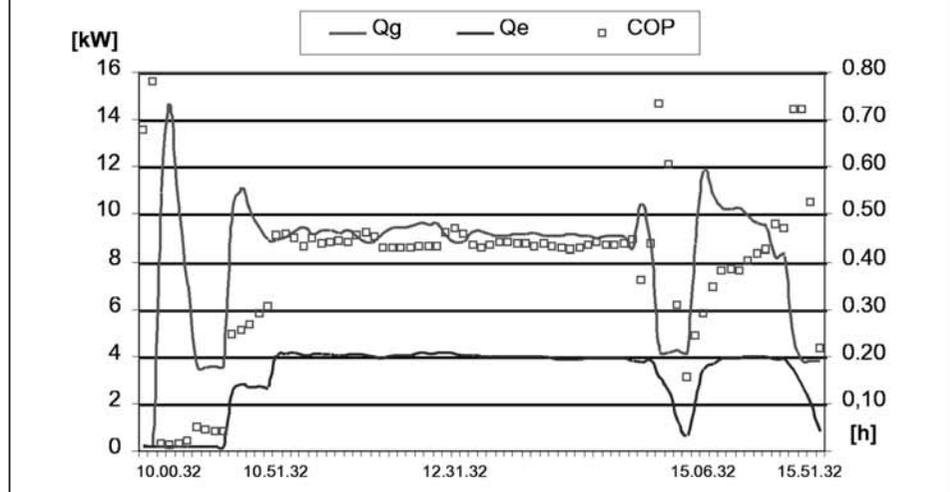
Finally, in Fig. 4 the normalized cooling capacity and the global COP are respectively sketched as a function of the evaporative cooling tower outlet re-cooling fluid temperature, setting the cooling circuit outlet temperature at 11 °C and the generator inlet temperature at 85 °C. All machines show bad performance at re-cooling temperatures higher than 35 °C, especially samples C and D.

The differences between the cooling capacity of the samples depend on the manufacturers' construction choices. Samples A and E are those the most influenced by their volumes, which considerably diminishes the relative capacity. Sample E shows poor performance at low cooling temperatures because of its intermittent functioning, which decouples the heat feeding and cooling production environments. Samples A and B behave similarly in terms of global COP, reflecting their common construction philosophy; it should be pointed out that samples A and E weigh twice as much as all the other absorption machines investigated

FIRST RESULTS OF AN EXPERIMENTAL PLANT

An experimental plant has been realized by the University of Perugia to feed an absorption chiller (D) with solar energy. First results highline how the

Figure 5. COP, Power supply (Q_g) and cooling power (Q_c) of Machine D ($T_{g,i} = 80$ °C, $T_{t,o} = 26$ °C).



machine can work with a generator inlet temperature of 80 °C if cooling inlet temperature is less than 35 °C, producing water chilled at 10 - 12 °C with a COP of almost 0.6. If cooling inlet temperature decreases under 30 °C, the chiller cools water down to 7 - 8 °C but COP becomes lower than 0.5. When the cooling inlet temperature in fact is lower than 30 °C, the generator is able to receive more heat than nominal one but only nominal heat is used by the evaporator to produce cooling power (Fig. 5). Extra heat is bypassed directly to the absorber in liquid form (overflow effect). Therefore, first results show that this machine can work properly (COP 0.5 - 0.6) with a generator inlet temperature lower than the nominal one (90 °C), if cooling inlet temperature is over 30 °C, whereas a lower cooling inlet temperature at the same conditions can decrease COP values under 0.5.

CONCLUSIONS

A survey of five small-size absorption chillers driven by solar energy is presented. The machines analyzed cover a range of cooling capacities (from 5 to 12 kW) and have different working principles and designs. The performance study was conducted starting from the manufacturers' rating and functioning curves, imposing the same working conditions and investigating their performance when the heat source comes from solar energy. The study has been conducted varying the three external temperatures (heat source, re-cooling

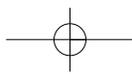
water and cooling water), taking into account of the dimensions of each sample. The results consist of a group of data that allow the definition of the five samples' performance in each working condition that the cooling load, the external environment and the sun impose on these chillers.

NOMENCLATURE

COP	coefficient of performance	(-)
rps	revolutions per second	(s ⁻¹)
M.U.	measurement unit	(-)
Q	heat power	(kW)
T	temperature	(°C)
Subscripts		
c	cooling	
g	generator	
i	inlet	
o	outlet	
t	evaporative cooling tower	

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Solar Cooling in the Unit for Development of Solar Equipments

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The unit for development of solar equipments is a state institution depending on the ministry of higher education and scientific research of Algeria. In this context, the principal missions of the unit are development of solar operated thermal and photovoltaic system and equipment using solar energy. The unit has two main research divisions, with the total of forty three (43) researchers, divided into height research group. The first division works on the development of systems and equipments using renewable energies. The second works on the development of refrigeration systems and equipment and water treatment using renewable energies.

Algeria has a very good geographical situation for solar energy applications. The daily sunlight averages the 10 hours/day,

with a daily average global radiation of 5 to 7 kWh/m²/day in most parts of the country and solar energy heating and cooling equipments will undoubtedly have very good prospect in the future. In this context, the principal missions of our unit are development of solar operated thermal and photovoltaic system and equipment using solar energy including solar cooling.

INTRODUCTION

Conventional cooling systems and air conditioning equipment consume near 15% of total electricity production. The manufacturing of cooling equipment with weak consumption energy or without conventional electricity contribute to reduce the CO₂ emission. The solar cooling technology is a good example of alternative kind of refriger-

ation system and it helps to reduce the environmental impact as no hydrocarbons are involved but the electricity is provided by the sun.

The expanding world population and the increasing demand for energy have brought serious problems for the world environment. Refrigeration has applications in a considerable number of fields of human life, for example the food processing field, the air-conditioning sector, and the conservation of pharmaceutical products, etc.

The conventional refrigeration cycles using the traditional vapor compression cycle contribute significantly in an opposite way to the concept of sustainable development.

The use of solar energy for environmental control is receiving much attention as a result of the projected world energy shortage.

Refrigeration using solar energy is a particularly attractive application because of the near coincidence of

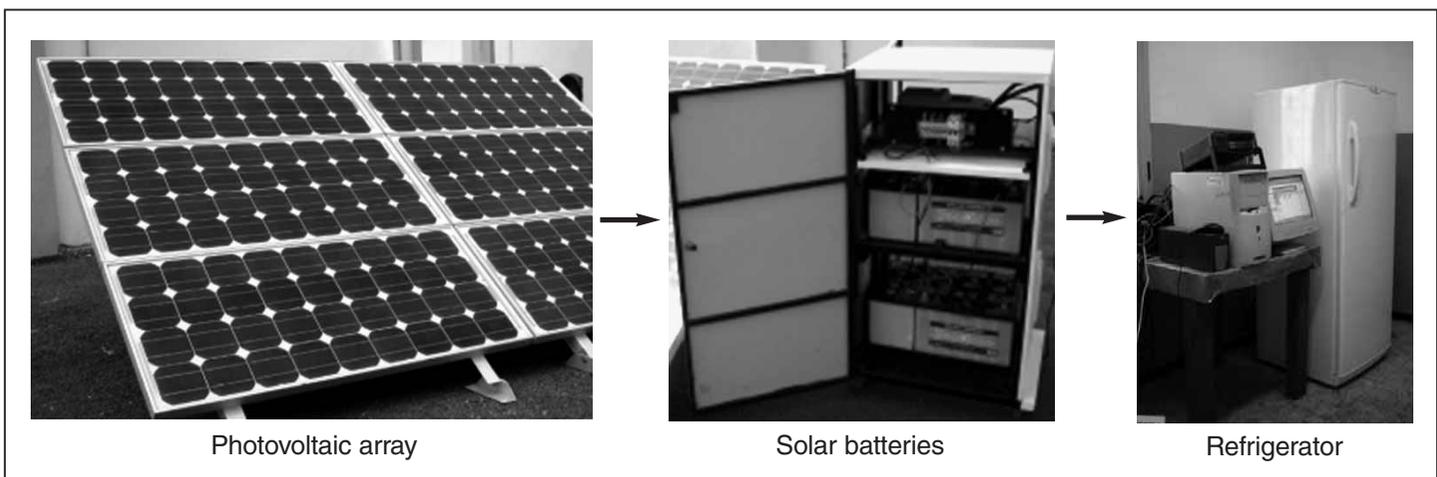
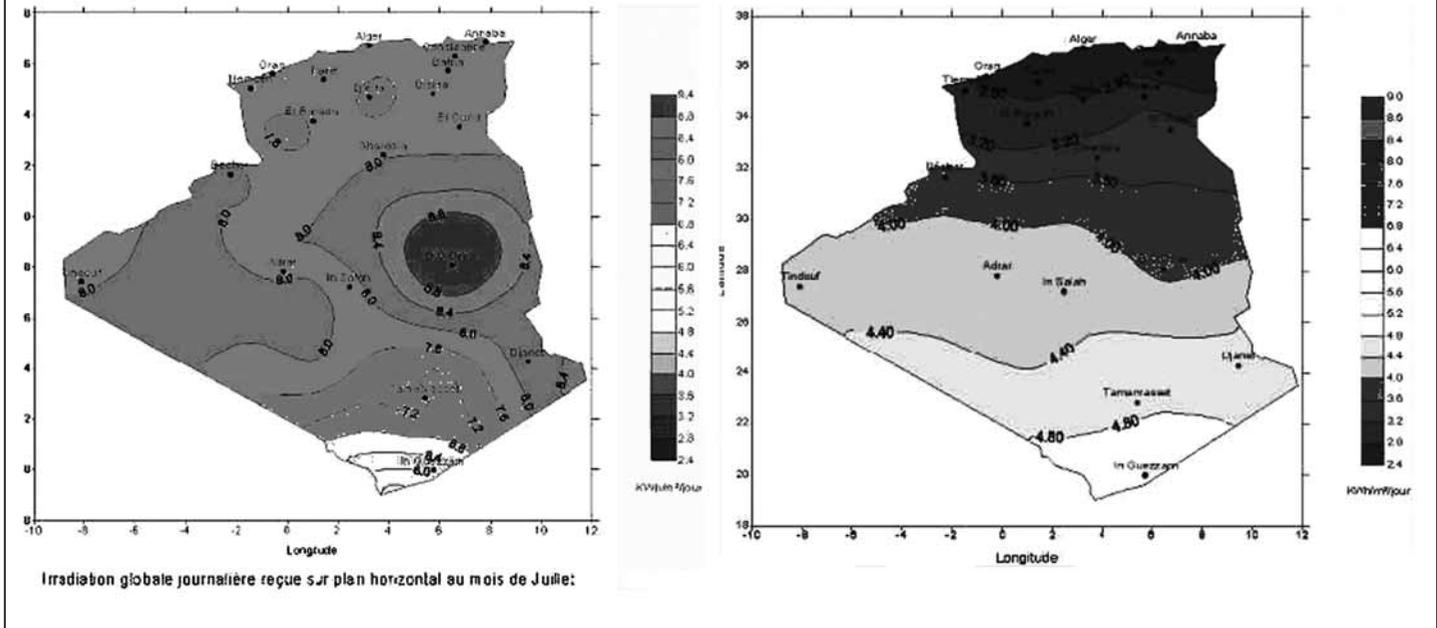


Figure 01. Geographical repartition of solar energy in Algeria (July and December).



peak cooling loads with the available solar power. Solar refrigeration has the potential to improve the quality of life of people who live in areas with electrical shortage.

The solar sorption cooling cycle is usually a preferable alternative. First, it uses thermal energy collected from the sun without the need to convert this energy into mechanical energy as required by the vapour compression

cycle. Second, it uses fluids, such as water or ammonia, with zero 'ozone depletion potential', which fulfill the Montreal Protocol. Third, the fluids have zero 'global warming potential' and fulfill the Kyoto Protocol.

In refrigeration, our division works on two axes, heat operated refrigeration systems and refrigeration and air conditioning using renewable electrical energy

Actually different projects are under way in order to develop solar operated thermal and photovoltaic system and equipment.

Among these projects we have:

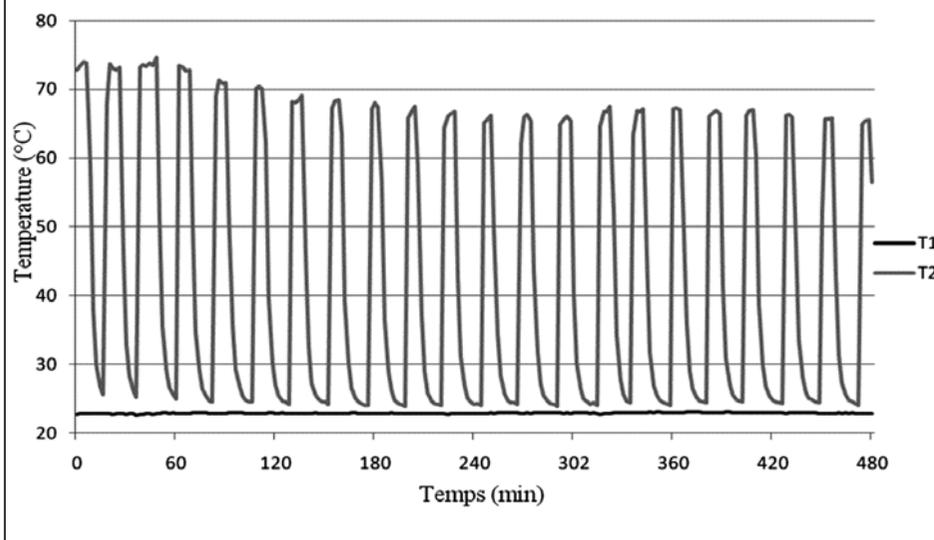
- Development of ice cube maker using solar energy.
- Humidifier and dehumidifier using PV system.
- Refrigerator with vapour compression cycle using PV system.
- Heat operated refrigeration system and equipment

Algeria has a very good geographical situation for solar energy applications. The daily sunlight averages the 10 hours /day, with a daily average global radiation of 5 to 7 kWh/m²/day in most parts of the country (see. Fig. 1), and solar energy heating and cooling equipments will undoubtedly have very good prospect in the future. Right now, a lot of research projects in research centers and state institutions are undertaken to develop equipments using renewable energies (1).

The research work on refrigeration in Unit for Development of Solar Equipments started in 1993, Several prototype refrigeration systems have been developed, photovoltaic driven domestic refrigerator, drinking water cooler, small vaccine storage refrigerator, humidifier ice maker and tested. This paper shows the various aspects researched in UDES.

Figure 1.

Shows the variation of the compressor body temperature of 50 Hz sinusoidal AC. It can be seen that the compressor body temperature goes through cyclic changes in accordance with the on-off cycle of the refrigerator albeit.



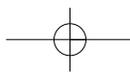
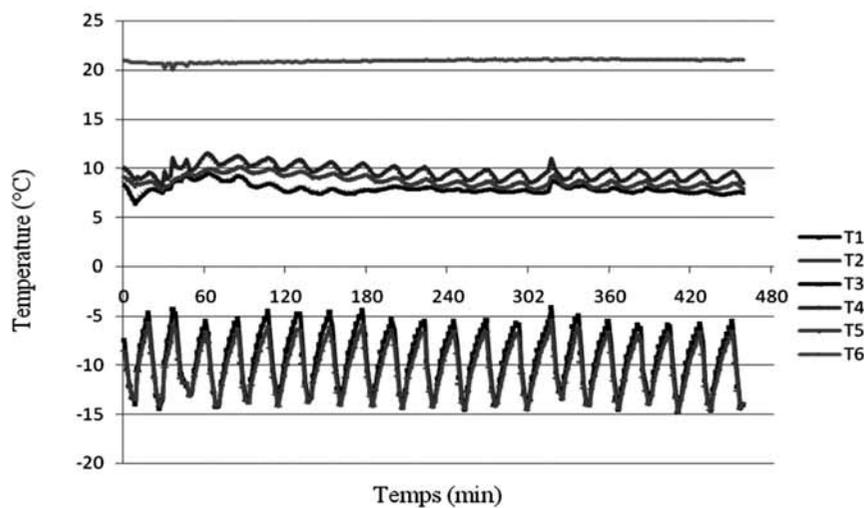


Figure 2.
Cool-down and warm-up characteristics of the refrigerator.



Legend: T1: upper freezer surface; T2: lower freezer surface; T3: lower cabinet; T4 upper cabinet; T5 middle cabinet; T6: ambient temperature.

daily global radiation of 5 to 6 kWh/m²/day) and a performance factor of: Pf = 0.6.

A set of six stationary batteries of 105 Ah/12 V each is used. The batteries are arranged to give a continuous output of 315 Ah /24 V, with three days autonomy and a lower discharge limit of 80 % on the batteries. Included in the PV system regulation are a charge regulator and an inverter. The power delivered by the PV system installed (900 VA) covers largely the electrical needs of the experimental setup.

SIMULATION OF AN AIR DEHUMIDIFIER BASED ON A VAPOUR COMPRESSION CYCLE

We are working actually on the design of a cooling and dehumidifying coil



Technical characteristics:
Dimensions (LxWxH): 610x520x1080 mm
Weight : 40 kg
Compressor consumption: 120 W
Voltage input: 12 V
Volume of refrigerated water: 30 l
Temperature range: 0 °C to 10 °C



Technical characteristics:
Intérieures (mm) : 480 x 400 x 330
Poids: 50 Kg
Tension d'alimentation: 24 VDC
Puissance du compresseur: 120 W
Volume d'eau réfrigérée: 63 litres
Plage de réglage de température (°C): -05 to +10°C
Dimension (L x l x H):
Extérieures (mm): 600 x 550 x 400

compartment of about 40 l volume and uses a capillary expansion device. Its overall dimensions are 1650x590x700 mm. A 25mm thick polyurethane foam insulation is provided all around. The inner liner of the refrigerator is PVC and the outer one is steel sheet with enamel paint finish. The thermostat of the refrigerator is fitted on the aluminum evaporator surface.

The calculated power of the PV field is based on the solar power potential of the south of the country (average solar



Technical characteristics:
Dimension (L x l x H):
Extérieures (mm): 835 x 565 x 1010
Intérieures (mm): 690 x 425 x 450
Poids : 60 Kg
Tension d'alimentation: 24 VDC
Puissance du compresseur: 120 W
Volume réfrigéré: 132 litres
Plage de réglage de température (°C): -20 à +10°C

CHARACTERIZATION OF A PHOTOVOLTAIC DRIVEN DOMESTIC REFRIGERATOR

The experimental system is the most widely used domestic refrigerator in our country which has an internal volume of 330 l, 0,2CV cooling capacity and works on R134a. It has a single door hinged on the right, a top freezer

(fig.3). This design is necessary because we are in the process of fabricating a small domestic dehumidifier based on a vapour compression cycle. A complete thermodynamics analysis has already been made(2).. Cooling the air below its dew point temperature is a common method of dehumidification.

As long as the coil surface tempera-



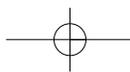
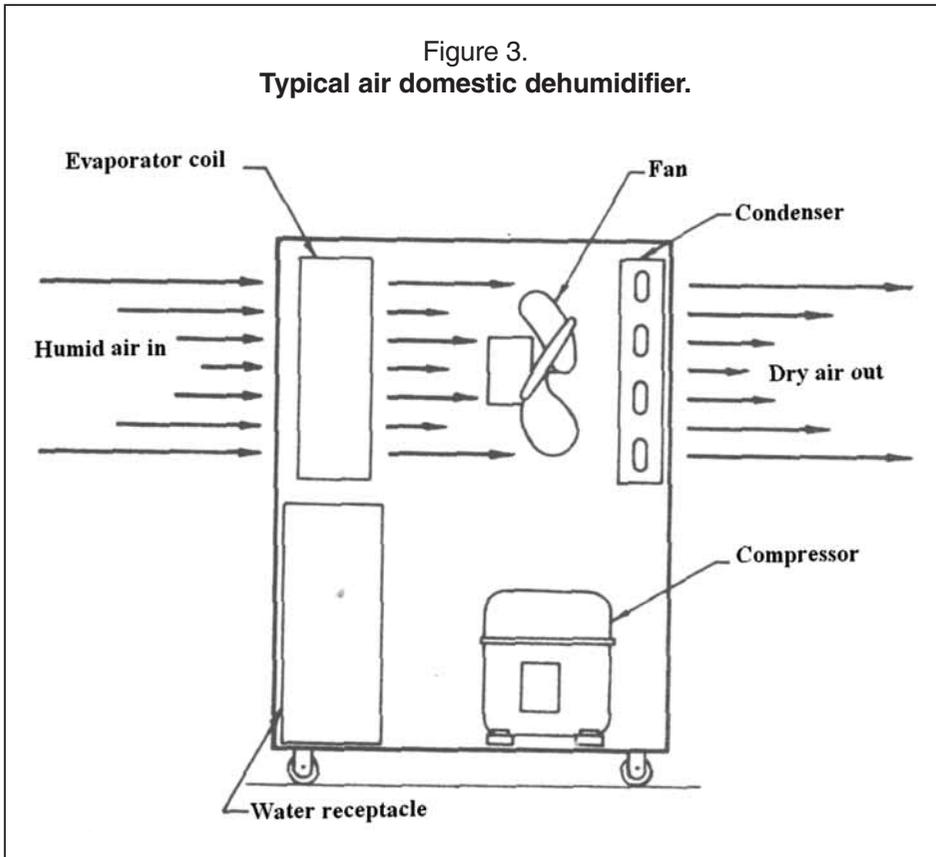


Figure 3.
Typical air domestic dehumidifier.



$$q_s = \dot{m}_a (h_a - h_2) \quad (7)$$

The total heat transfer from the moist air is then:

$$q = q_s + q_l$$

This is the total amount of heat transfer from the moist air. Using this quantity for the total heat transfer, we can easily find a condensing unit to match up.

The use of refrigeration is a practical and economical method for air dehumidification when the air is relatively warm with high moisture content. Domestic air dehumidifiers using a vapor compression cycle are quite popular, but new restrictions on refrigerants and energy consumption are paving the way to a lot of research and future development in this field.

The conceptual design for the heat transfer surface is underway. A prototype of a domestic air dehumidifier is under consideration.

HUMIDIFIER (adiabatic saturator)

The housing is made for pre-painted sheet metal. The back side of the housing contains a fibrous materials kept saturated with water.

A pump lifts water from the sump

ture is kept below dew point temperature of the entering air, cooling and dehumidification will occur.

Although the actual process is complicated and vary considerably depending on the type of the heat exchange surface, the surface temperature and the flow conditions, the heat and mass balance can be expressed in terms of initial and final states of the air

$$\dot{m}_a \cdot W_1 = \dot{m}_w + \dot{m}_a \cdot W_2 \quad (2)$$

Combining these two equations we get:

$$\dot{q} = \dot{m}_a (h_1 - h_2) - \dot{m}_a (W_1 - W_2) \cdot h_w \quad (3)$$

The cooling and dehumidification process involves both sensible and latent heat transfer where the sensible heat transfer is associated with the decrease in dry bulb temperature and the latent heat transfer is associated with decrease in humidity ratio.

We can write:

$$q_s = \dot{m}_a c_p (T_1 - T_2) \quad (4)$$

$$q_l = \dot{m}_a (W_1 - W_2) \cdot h_{fg} \quad (5)$$

We can also write:

$$q_1 = \dot{m}_a (h_1 - h_a) \quad (6)$$

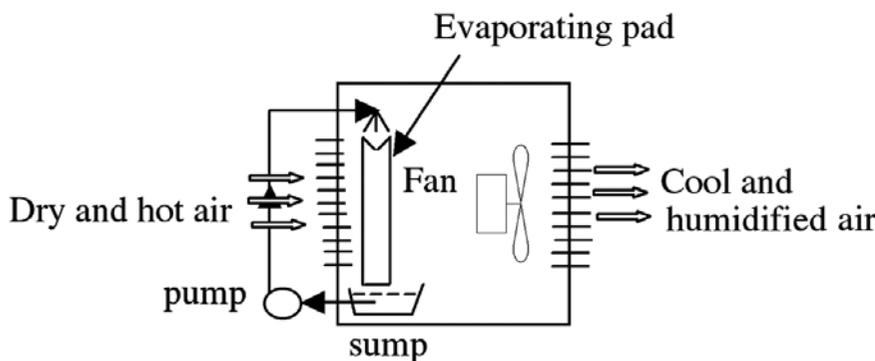
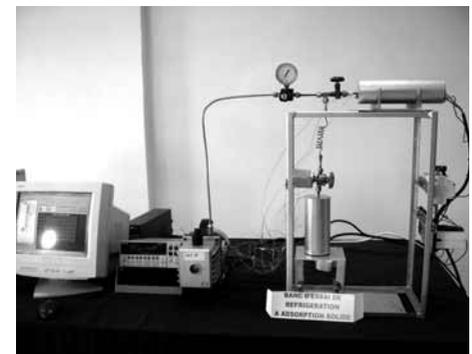
Thermodynamic analysis

(1st Law Analysis)

The energy balance around the coil:

$$\dot{m}_a \cdot h_1 = \dot{q} + \dot{m}_a \cdot h_2 + \dot{m}_w \cdot h_w \quad (1)$$

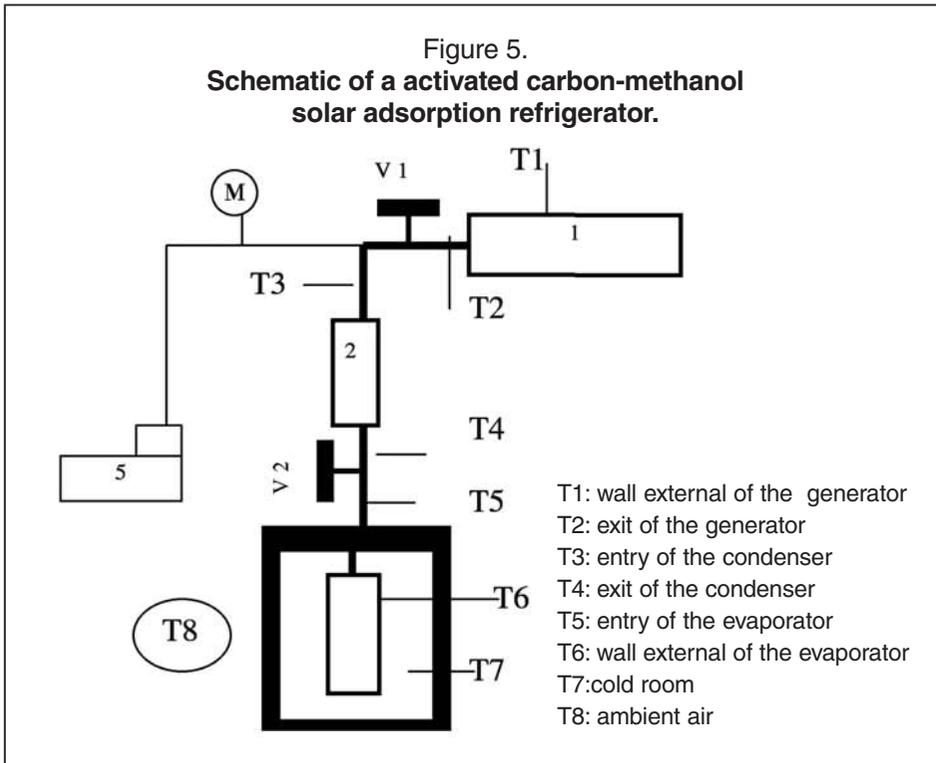
The mass balance around the coil



Prototype



We realized, for this purpose, the following experimental device:



micro-pilot show (fig.7) that by using solar energy, can be used for the conservation of food and this for one relatively important duration⁽³⁾.

CONCLUSION

The various achievements presented, show that UDES strongly activates in favour of the promotion of renewable energies, with less impact on the environment. The research projects undertaken are directed toward the development of refrigeration and air conditioning equipments and systems using solar energy and refrigerants with less global warming and ozone depletion potential

Aknowledge

Special thanks to Ms S. Bouadjab and M. Chikh for their help in dimensioning of the PV systems

located in the bottom of the housing and delivers it to a perforated channel located at the top.

The water drips through the evaporated paid to keep it wet and is collected back in the sump located in the bottom of the housing. A motor driven fan draws outside air through the evaporative pad. Humidifying efficiency = actual dry bulb change / theoretical dry bulb change

ADSORPTION REFRIGERATOR

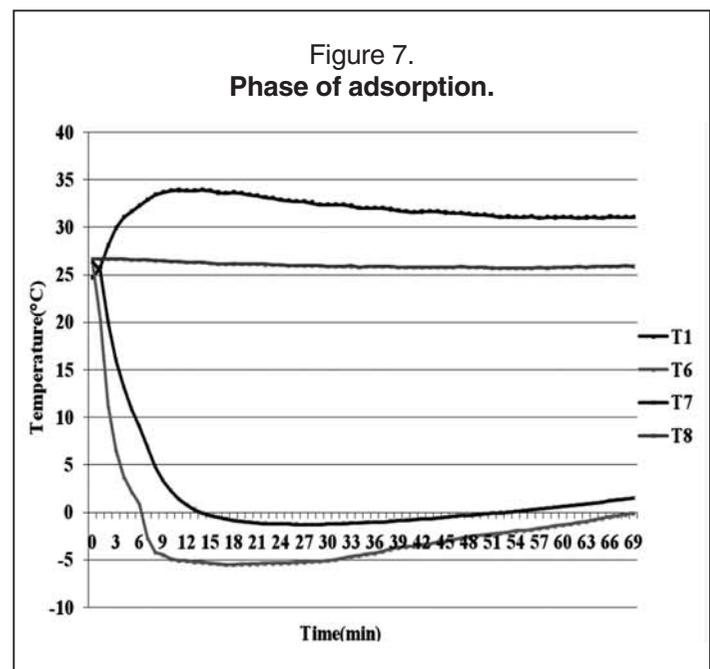
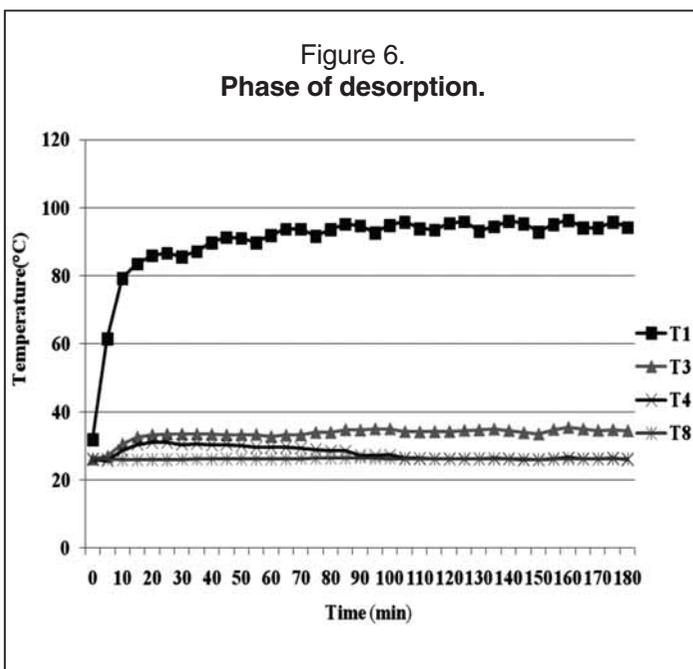
Experimental set-up of an adsorption refrigerator using activated carbon-methanol. The solar heating is simulated with an electric heater

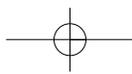
The installation comprises 59g activated charcoal saturated with methanol. The volume of the cold room is of 120cc

The various tests carried out on this

REFERENCE

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Sustainable Refrigeration

PAUL HOMSY

Nestlé

Refrigeration is Essential for the Food Industry

In line with its environmental policy, Nestlé is committed to minimising the impact of its industrial operations on the Environment. This includes the choice of the technologies the Company uses in its 480 factories worldwide and, among these, Refrigeration. Without refrigeration in manufacturing, storage and distribution, modern food production would not be possible. Today, there are several major product sectors where refrigeration is widely used, including dairy, ice cream, frozen & chilled foods and freeze-dried instant coffee.

Setting the Trend in Industrial Refrigeration

Since 1998, the use of natural refrigerants has increased, in particular the revival of carbon dioxide in industrial refrigeration. For low temperature food applications, ammonia (NH₃) in combination with carbon dioxide (CO₂) in a "cascade" refrigeration system can improve manufacturing plant efficiency and safety, thus increase the safety of Employees, Neighbours and the



Beauvais CO₂ / NH₃ machine room.

Environment.

Significant efforts have been undertaken to accelerate the phase out of HCFC's, well ahead of the Montreal Protocol and EU requirements. For example in 2000, Beauvais (France) 80'000 m³ cold store operating at -30°C



World first CO₂ continuous ice cream freezer tested in Thailand.

has been converted to natural refrigerants, NH₃ in the machine room and CO₂ distributed as a two phase brine in the cold rooms.

In 2001, another major milestone was set in the revival of CO₂ in industrial refrigeration by converting Hayes coffee freeze drying factory in the UK from R22 to an innovative CO₂/NH₃ cascade system. The groundbreaking Hayes project caused a snowball effect and today there are hundreds of industrial CO₂/NH₃ cascade systems operational in the world.

In 2003, a new Frozen Foods plant was opened in Jonesboro (USA). A CO₂/NH₃ cascade, the largest in the world, was again installed successfully. In 2005 Gram's world first continuous ice cream freezer operating on CO₂

was tested in Bangchan factory in Thailand. The main challenge was to field test a reliable CO₂ freezer that would operate satisfactorily with a different refrigerant, different pressure, different settings, different valve sizes, etc, and having different heat exchange properties with an unknown impact on the product quality.

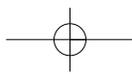
Developing Sustainable Solutions for Smaller Refrigeration Units

While the efforts to promote natural refrigerants are mainly focused on industrial applications, Engineers and Researchers are also actively searching for appropriate technical solutions that are safe, legally accepted and cost effective, for smaller commercial refrigeration systems. To this end, Nestlé is collaborating closely with major equipment suppliers and through International Organisations and with Academic Institutions, promoting natural refrigerants.

Confirming the Policy on the Use of Natural Refrigerants

In April 2008, Nestlé's most Senior Operations Manager issued a reminder letter to all operations worldwide confirming the commitment to the use of natural refrigerants that are environmentally friendly. Whenever feasible, Carbon Dioxide in combination with Ammonia must be used for all low temperature applications and water or glycol chillers with ammonia as primary refrigerant must be used for all positive temperature applications.





Magnetic Refrigeration at Room Temperature

PETER EGOLF

RONALD ROSENSWEIG

University of Applied Sciences of Western Switzerland

Chaires Internationales de Recherche Blaise Pascal

The University of Engineering and Economy of the Swiss County of Vaud offers in Yverdon-les-bains (French part of Switzerland) eight directions of University educations in the domain of Engineering and the Economy of Enterprises. With 1500 students it is the largest entity of the Haute Ecole Spécialisée de Suisse Occidentale (Hesso). In all its divisions professors with their staff are performing high quality research and development for the (local) industry, but also on an international level, numerous of them with good recognition. Prof. Peter W. Egolf and Prof. Osmani Sari are leaders of the Theory and Numerics Division (SIT) and an Experimental Laboratory (TIS) of the Thermal Sciences Institute (IGT), respectively. Dr. Andrej Kitanovski is responsible for magnetic heating and refrigeration in the Theory and Numerics Division of IGT.

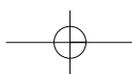
Magnetic refrigeration is an adiabatic cooling method which applies the magnetocaloric effect (MCE). From the point of view of basic physics, it shows an analogy to the conventional gas compression/expansion method. It has been applied for many years in cryogenics, to reach very low temperatures. In 1976, Brown presented the first room temperature refrigerator applying adiabatic magnetization and demagnetization.¹ After the discovery of the “giant” magnetocaloric effect (GMCE) in $Gd_5(Si_2Ge_2)$ in 1997 by Gschneidner and Pecharsky,² which increases the MCE, many scientists and industrial representatives of the refrigeration community concede that this “new” technology (applying permanent magnets and the GMCE) has a good future potential for a remarkable penetration into the refrigeration market. They are convinced that in several different market domains, conventional refrigeration could be replaced by magnetic refrigeration. The main reason for such an attitude is the possibility to replace the HFC refrigerants by environmentally benign magnetocaloric alloys. HFCs, with a typical global warming potential (GWP) of 1000 to 3000 times that of CO_2 , at present show an increasing sales market, which has its cause in the phasing out of the more destructive HCFCs and CFCs. This phasing out process is still ongoing and in most developing countries HCFCs and CFCs are still allowed. Systems with natural refrigerants (ammonia, CO_2 , propane, etc.) are good solu-

tions for numerous applications, but to date, none of them have reached a remarkable breakthrough on a wide scale of applications in refrigeration. Other advantages include the higher cycle efficiencies of magnetic refrigeration processes compared with those of gas-compression refrigeration and the noiseless operating conditions of a magnetic refrigerator. This IIR informative note briefly highlights the state-of-the-art, the advantages and disadvantages of this promising technology.

INTRODUCTION

The refrigeration-technology market is closely related to beverage and food production, industrial process, the chemical and pharmaceutical industry, the automotive sector, etc. Some of these sectors have strongly growing markets, thanks to the rising incomes of Eastern European, Indian and Chinese customers, with their desire for modern consumer goods driving such development. The retail market, supermarket and hypermarket chains are strongly benefiting from this development. Because the number of built alternative refrigeration technologies such as absorption or adsorption refrigeration, thermoelectric and thermoacoustic refrigeration, etc. is negligible, this leads to positive prospects for the gas-compression system producers.

Furthermore, the tendency to cool domestic buildings in southern areas



is also increasing. The business-as-usual scenario, based on dynamic numerical climatological system simulations, was published by the European Commission. The prediction for the year 2010 is an HFC emission level the equivalent of 66 Mtonnes CO₂. This is an increase of 62% based on the value of 1995. Refrigeration and air conditioning are responsible for the main fraction, namely 43%. What are the alternatives, if HFCs also will have to be reduced? This is a desire of an increasing number of politicians that already has been announced in some countries. Maybe new less harmful refrigerants will be discovered. A new blend H has just been developed and announced by an industrial company, but up until now, reliable experience is missing.

The time would be ideal for an alternative refrigeration technology such as for example magnetic refrigeration. For the interested reader, who wants to gain a greater insight into magnetic heat pumps and refrigerators than given in this short informatory note, several review articles are available.³⁻⁷ This promising technology works without a gaseous refrigerant and its energy efficiency (coefficient of performance, COP) in principle can be higher than that of a conventional refrigeration system. As a result, its breakthrough in certain domains of the refrigeration market would lead to less CO₂ output into the atmosphere. This informatory note gives an overview of

this spectacular technology, discusses ideal and not-so-promising applications and reports on some problems which have to be solved in order to enter industrializing phases for the various refrigeration applications envisaged.

THE MAGNETOCALORIC EFFECT

A magnetocaloric material may provide three different contributions to the total entropy, a magnetic, an electronic and a lattice contribution.³ The entropy is a measure of order in the magneto-thermodynamic system. A high order is related to a low entropy and vice versa. Dipoles, i.e. electronic spins, may show different orientations. If in a paramagnet, ferromagnet or diamagnet these entities are oriented in the same direction, the order and also the magnetization is high. It is clear that applying a magnetic field aligns electronic spins, and lowering the temperature (by releasing energy from the system) also leads to a more ordered system. Therefore, in the sense of the theory of critical phenomena the external magnetic field yields the stress parameter and the magnetization the order parameter of such magnetic materials.

In Figure 1, the magnetization of pure gadolinium is shown as a function of the "magnetic field" $\mu_0 H$ and the temperature T . If all the moments or spins are aligned, the maximal magnetiza-

tion M_{\max} occurs. The actual magnetization $M(T,H)$ is divided by this maximal value $M_{\max} = 2.47$ T (tesla) to obtain the normalized magnetization $\hat{m} = M/M_{\max}$. The temperature is also normalized; it is divided by the Curie temperature T_c of the material: $\hat{t} = T/T_c$. For gadolinium, the Curie temperature is just at room temperature, namely at $T_c \cong 293$ K. The maximal magnetization ($\hat{m} = 1$) occurs at the absolute zero point ($T = 0$ K or $\hat{t} = 0$), independent of the applied magnetic field. At higher temperatures, the magnetization is lower. And here one can observe a magnetic field dependence. It is clear that a higher field leads to a higher ordering, respectively a higher magnetization \hat{m} .

If a magnetocaloric material is moved into a magnetic field, this is usually a fast process. Practically no heat will be exchanged with the environment. Then for this adiabatic process the total entropy s - which in usual cases is the sum of the magnetic s_M , electronic s_E and lattice entropy s_L - remains constant: $s = s_M + s_E + s_L = \text{const.}$ ³ But the magnetization increases. This means that the magnetic entropy s_M decreases. Therefore, the remaining electronic and lattice entropies, s_E and s_L , must increase. By spin lattice couplings - which occur in milliseconds - phonons or lattice vibrations are created. These oscillatory movements may be compared with Brown's motion of atoms or molecules in a gas. They increase the temperature of the

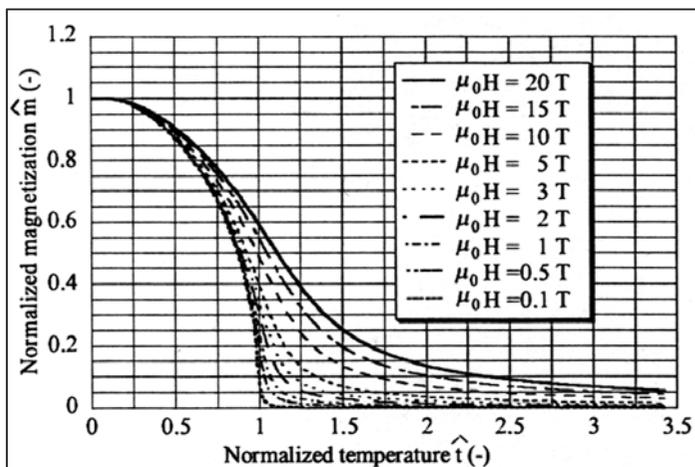


Figure 1. The normalized magnetization curves of pure gadolinium for different "magnetic fields" $\mu_0 H$. The quantity μ_0 is the permeability of vacuum. This figure was taken from Reference⁹.

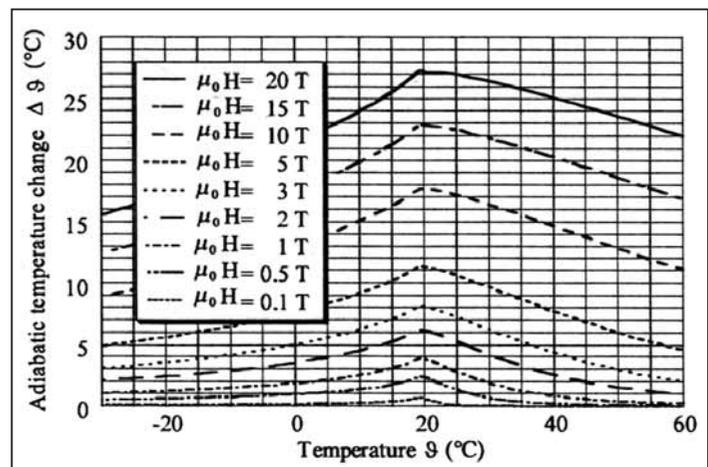
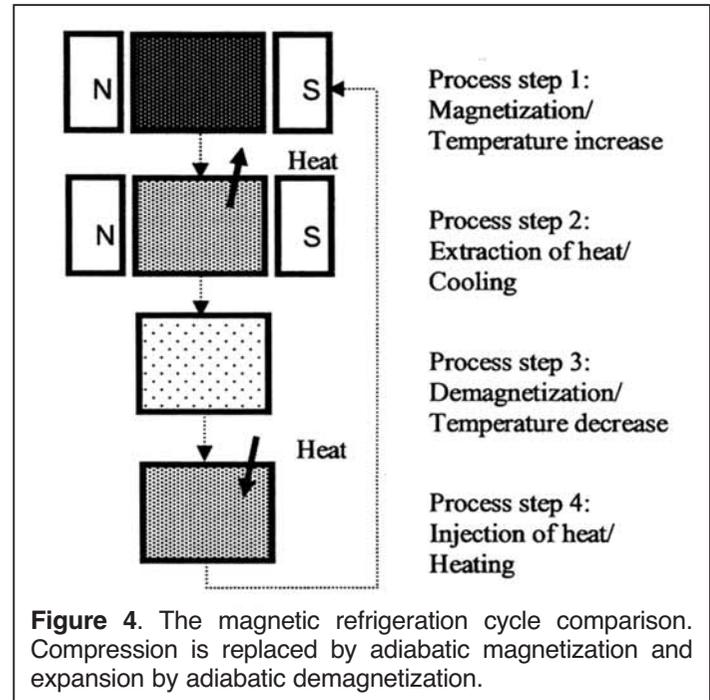
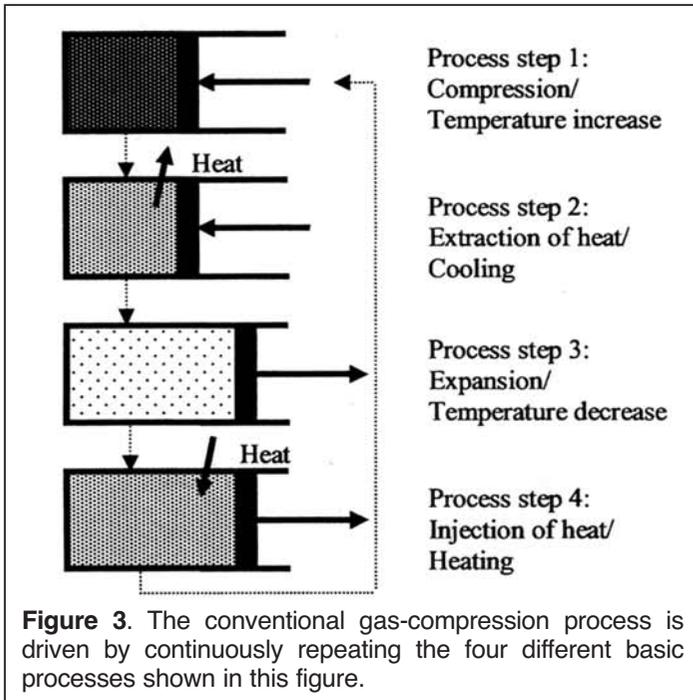


Figure 2. The adiabatic temperature change of gadolinium in the vicinity of the Curie temperature $T_c \cong 20$ °C. As in Figure 1, here also, the internal field $\mu_0 H$ is shown (from Reference⁹).



solid material. Now it becomes clear that removing the magnetocaloric material from the magnetic field lowers its lattice vibrations and its temperature, because now the magnetic moments and spins take up energy from the lattice and become disordered again. The achievable temperature increases $\Delta\vartheta$ of gadolinium for “magnetic field” changes $\mu_0 H$ of 1 and 2 T are shown in Figure 2. For both field changes, the temperature decrease occurs at the higher temperature $\vartheta + \Delta\vartheta$, with the same absolute value of the temperature change, $|\Delta\vartheta|$, in the heating and cooling case.⁸ For a magnetic refrigerator with permanent magnets of reasonable weight, 2 T is at present the maximal obtainable “magnetic field” strength. For zero magnetic field, the described process is a second order phase transition. For higher magnetic fields, this transition becomes continuous. The described exchange of degrees of freedom between the magnetic moment/spin and the lattice system is the key process for magnetic refrigeration. It was discovered in 1881 by the German physicist Emil Warburg.

PROCESSES OF MAGNETIC REFRIGERATION

In Figure 3 the four basic steps of a conventional gas-compression/expansion

refrigeration process are shown. These are a compression of a gas, extraction of heat, expansion of the gas, and injection of heat. The two process steps extraction of heat and expansion are responsible for a cooling process in two steps. The main cooling usually occurs through the expansion of the gas.

The steps of a magnetic refrigeration process are analogous. By comparing Figure 3 with Figure 4, one can see that instead of compression of a gas, a magnetocaloric material is moved into a magnetic field and that instead of expansion it is moved out of the field.

As explained in the previous section, these processes change the temperature of the material and heat may be extracted, respectively injected just as in the conventional process.

There are some differences between the two processes. The heat injection and rejection in a gaseous refrigerant is a rather fast process, because turbulent motion transports heat very fast. Unfortunately, this is not the case in the solid magnetocaloric materials. Here, the transport mechanism for heat is slow molecular diffusion. Therefore, at present filigree porous structures are considered to be the best solution to overcome this problem. The small distances from the central regions of the material to an adjacent fluid domain, where a heat

transport fluid captures the heat and transports it out of the material, are ideal to make the magnetic cooling process faster. Furthermore, the not very large adiabatic temperature differences of magnetocaloric materials will require more often a design of cascade or regenerative magnetic refrigerators⁸ than in conventional refrigerators and hence require additional heat transfer steps.

MAGNETOCALORIC MATERIALS AND THEIR PROPERTIES

To apply the magnetocaloric effect with a high performance, optimal properties of magnets and magnetocaloric materials are required. For this, the different families - which show a large GMCE - have to be taken into consideration. The properties of presently best magnets can not be discussed in this brief note, but they are described in the literature: see Reference⁶ for instance.

Pure gadolinium may be regarded as being the ideal substance for magnetic refrigeration, just as the ideal gas is for conventional refrigeration. But just as conventional systems are usually not operated with ideal gases, magnetic refrigerators will perform better with specially designed alloys (see below). One advantage of pure gadolinium is that its physical proper-

ties may be described by basic physical laws such as the Brillouin function for the magnetization or the Debye function for the specific heat, etc. This allows the numerical calculation of magnetothermodynamic charts of high resolution.⁹ To produce such charts for magnetocaloric alloys would demand a tremendous amount of high-quality experimental data, which usually is not available. Therefore, it generally makes sense to begin initial testing of a magnetic refrigerator prototype with a gadolinium filling. After the teething problems of a new machine have been solved with the gadolinium content, the latter may be replaced by better magnetocaloric alloys.

Gschneidner and Pecharsky¹⁰ have published the following list of promising categories of magnetocaloric materials for application in magnetic

refrigerators:

- binary and ternary intermetallic compounds
- gadolinium-silicon-germanium compounds
- manganites
- lanthanum-iron based compounds
- manganese-antimony arsenide
- iron-manganese-arsenic phosphides
- amorphous fine met-type alloys (very recent).

At present, a number of toxic substances in such compounds are being replaced by more acceptable elements. A discussion on the different types of materials with their distinct properties is found in extended topical reviews.^{4,10} Currently, the total entropies and the related refrigeration capacity, the adiabatic temperature change and the costs of the materials are under investigation. Brück states that in the near future, other properties

such as corrosion resistance, mechanical properties, heat conductivity, electrical resistivity, and the environmental impact will also become important.⁴

Currently, the best, not too expensive materials were reported with cooling capacities at a change of 2 T “magnetic field” strength of approximately 1500 J/kg at constant temperature⁹ and an adiabatic temperature change of 7-8 K. Materials with low magnetic hysteresis are favourable, because the area of a hysteresis curve on coordinates of M vs. H corresponds to energy dissipated to the environment in each cycle.

MAGNETOTHERMODYNAMIC MACHINES

Application of the GMCE calls for a

Magnetic refrigerator prototypes are closer to the market

Up-to-present about thirty magnetic refrigerator and heat pump prototypes have been built, tested and described in the technical and scientific literature. Practically all of them are discussed in a new review article written by Yu

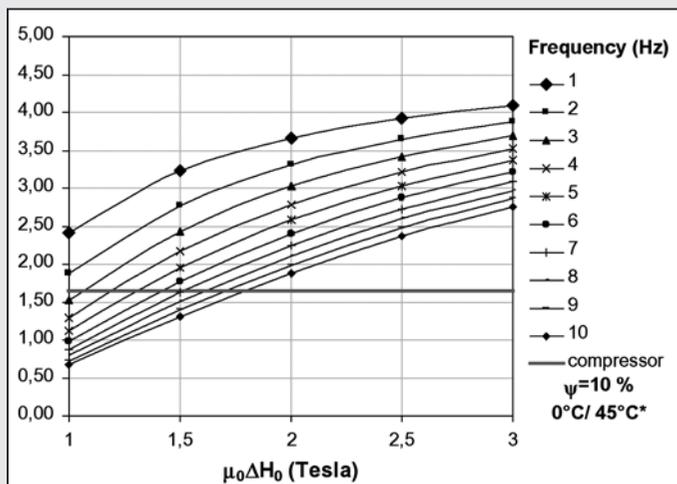


Fig. 1. The coefficient of performance, COP, of a magnetic household refrigerator as a function of the magnetic field density (presented as an induction) and its frequency of operation are shown (from Ref. [2]). The coefficient of performance of the conventional machine naturally shows no dependence on the magnetic field (as such a field is not present in such a device) and, therefore, appears in this figure as a constant.

et al. [1]. The first prototypes were mainly built with expensive and energy consuming superconducting magnets. At the beginning of their development magnetic refrigerators with permanent magnets were poor in performance (low cooling load) or they could not reach lower temperatures. In other machines the magnetocaloric materials were often mounted into the machines in form of packed beds, which usually leads to much too high pressure losses of the fluid flows, and therefore destroys the advantage of a better performance compared to conventional refrigerators with compressors. The predicted competitiveness of magnetic refrigerators with conventional refrigerators containing a compressor has been studied by theoretical modeling and simulation and is shown in Fig. 1. Other prototypes were based on the active magnetic regenerator (AMR) cycle. Several of these machines show a good temperature drop in a «pumping process», but without responding on any external load.

At the University of Applied Sciences of Western Switzerland up-to-present one magnetic refrigerator with a rectilinear magnetocaloric material load and two prototypes with rotating porous structure wheels have been designed, calculated, built and measured (one earlier and still heavy model is shown in Fig.'s 2 and 3). At present a new machine is being built in collaboration with Christian Muller and his team in the enterprise Cooltech Applications in Strasbourg, France. He is the Laureate of the 2007 prize of future entrepreneurs of the Eastern region of France. Additionally, a heat pump of 8 kW heating power for minergy houses (minimal energy houses) with ground heat sources for the Swiss market is under development. This large project is financed by the Swiss County of Vaud and the Swiss Federal Office of Energy in Berne.

magnetic field change in a magnetocaloric material. This can be performed using different magnetic refrigeration principles:

- alternatively changing magnetic fields in static blocks of magnetocaloric material by application of electromagnets
- rectilinear motion of magnetocaloric material with static permanent magnet assemblies
- rectilinear motion of permanent magnet assemblies with static magnetocaloric material blocks
- rotary motion of magnetocaloric material with static permanent magnet assemblies
- rotary motion of permanent magnet assemblies with static magnetocaloric material blocks.

The basic magnetothermodynamic cycles are the Carnot cycle, the Brayton cycle and the Ericsson cycle.

A review of the magnetothermodynamics of magnetic refrigeration is given in Reference 8. Also, cascade and regeneration processes are explained. Another concept is the application of the active magnetic refrigeration principal (AMR).¹⁰

Until now, studies on 28 prototypes have been published and some of their characteristics were listed (for a partial overview, see Reference¹⁰). One of the most successful machines was built by Astronautics Corporation, USA, and is shown in Figure 5.

This rotary type of magnetic refrigerator is operated with a frequency of up to 4 Hz. It has a magnetic field induction of 1.5 T, is filled with gadolinium spheres and has a cooling capacity of 95 W with a maximum temperature span of 20 K.¹⁰ Other prototypes have been built by the Material Science Institute in Barcelona, Spain; Chubu

Electric/Toshiba, Yokohama, Japan; a group at the University of Victoria, British Columbia, Canada; Sichuan Institute of Technology/Nanjing University, Nanjing, China; the Laboratoire d'Electronique Grenoble in Grenoble and Cooltech Applications, France.¹¹ The prototype designed by the University of Victoria applies the layered bed technique with two different materials. By choosing different alloys at different positions in the refrigerator, the performance of the refrigerator is increased. The refrigerator prototype built at the Sichuan Institute of Technology was the first which applied a material with the GMCE exceeding the adiabatic temperature difference of gadolinium.

ADVANTAGES AND DRAWBACKS



Fig. 2. The design of a prototype developed in the Thermal Science Institute of the University of Applied Sciences of Western Switzerland. This machine is based on the rotation principle. The magnets may be seen on the left back 180°. The front right side contains no magnet assembly and, therefore, yields the region with no magnetic field. Tubes for the heat transfer fluids are shown. In the cylinder above the magnetocaloric ring a motor to drive the refrigerator is assembled.

In other laboratories throughout the world also newer prototypes are under development, and it is expected that their operation characteristics will be substantially improved. Also the mass of the magnets will be very much decreased compared with the mass of the ancient and present prototypes. This is important, because of the not negligible prices and weights of the magnetic substances and compounds. Only by this magnetic refrigerators may also become economically feasible. Such newer prototypes will be presented to the public in one to two years time. After that further improvements will be necessary, also occupying about the same time period until



Fig. 3. After winning the first prize of the Swiss Technology Award 2006 and Special Prizes donated by the Swiss Federal Office of Energy and the Enterprise ABB Switzerland, the three inventors in red shirts from the left to the right (Prof. Peter W. Egolf, Dr. Andrej Kitanovski and Prof. Osmann Sari) are explaining the magnetic refrigerator prototype to the Swiss Minister for Economy, Joseph Deiss, at the world largest industrial fair in Hannover, Germany.

then finally first industrial prototypes will appear in some refrigeration markets.

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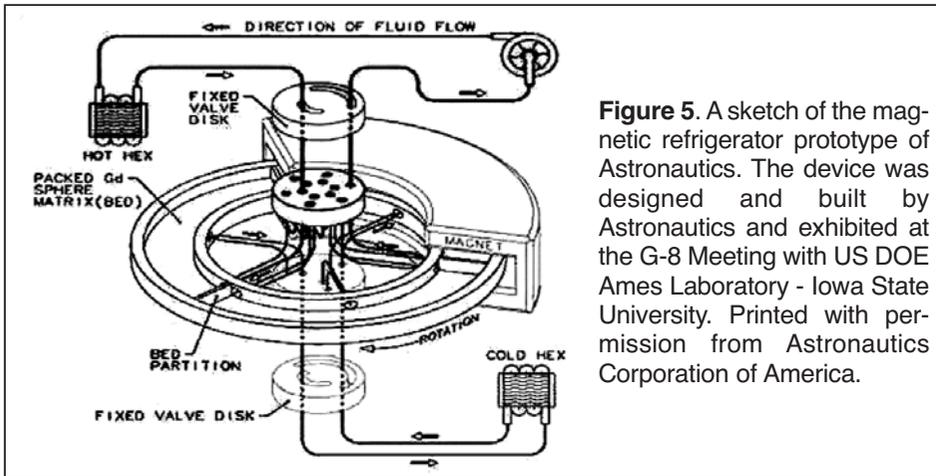


Figure 5. A sketch of the magnetic refrigerator prototype of Astronautics. The device was designed and built by Astronautics and exhibited at the G-8 Meeting with US DOE Ames Laboratory - Iowa State University. Printed with permission from Astronautics Corporation of America.

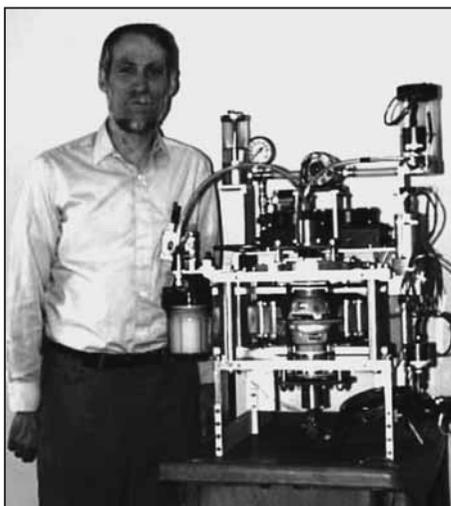


Figure 6. A pioneer of magnetic refrigeration, Dr Carl Zimm, at Astronautics beside the built magnetic refrigerator prototype, which is schematically shown in Figure 5. Printed with permission from Astro-nautics Corporation of America.

The potential advantages of magnetic refrigeration are valid in comparison with the direct evaporation refrigerating machines:

- “green” technology, no use of conventional refrigerants
- noiseless technology (no compressor). This is an advantage in certain contexts such as medical applications
- higher energy efficiency. Thermodynamic cycles close to Carnot process are possible due to the reversibility of the MCE
- simple design of machines, e.g. rotary porous heat exchanger refrigerator
- low maintenance costs
- low (atmospheric) pressure. This is an advantage in certain applications such as in air-conditioning and refrigeration units in automobiles.

On the other hand, some disadvantages include:

- GMCE materials need to be developed to allow higher frequencies of rectilinear and rotary magnetic refrigerators
- protection of electronic components from magnetic fields. But notice that they are static, of short range and may be shielded
- permanent magnets have limited field strength. Electro magnets and superconducting magnets are (too) expensive
- temperature changes are limited. Multi-stage machines lose efficiency through the heat transfer between the stages
- moving machines need high precision to avoid magnetic field reduction due to gaps between the magnets and the magnetocaloric material.

POSSIBLE FUTURE APPLICATIONS

The list of possible applications involves all domains of refrigeration, heat pump technology and power conversion. But there are two conditions which limit the applications of the technology in its current state. The first is the temperature span. If the difference between the upper and lower temperature levels is large, then the number of stages becomes also large and a practical realization is no longer economic. The second condition is the stability of the running conditions. Because the MCE is limited to a domain around the Curie temperature where the continuous phase transition occurs, it is difficult to operate magnetic refrigerating

machines under highly fluctuating conditions. More or less stable temperature levels are required for a reliable and efficient operation of a magnetic refrigeration system. The potential for cost-effective magnetocaloric air-conditioning systems was outlined by Russek and Zimm in the Bulletin of the IIR.¹²

CONCLUSION

Magnetic refrigeration is undoubtedly a promising technology that should be encouraged because of its numerous advantages, in particular energy saving and environmental benefits. Efficient prototypes for specific applications must now be built so that the refrigeration industry can be convinced to enter industrializing phases for the production of new magnetic refrigerators.

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*This Informatory Note was prepared by Peter W. Egolf, President of the IIR Working Party on Magnetic Cooling, and Ronald E. Rosensweig, former Chaire Blaise Pascal, Paris and author of Ferrohydrodynamics.*¹³ This note was reviewed by a number of IIR and IEEE experts worldwide.



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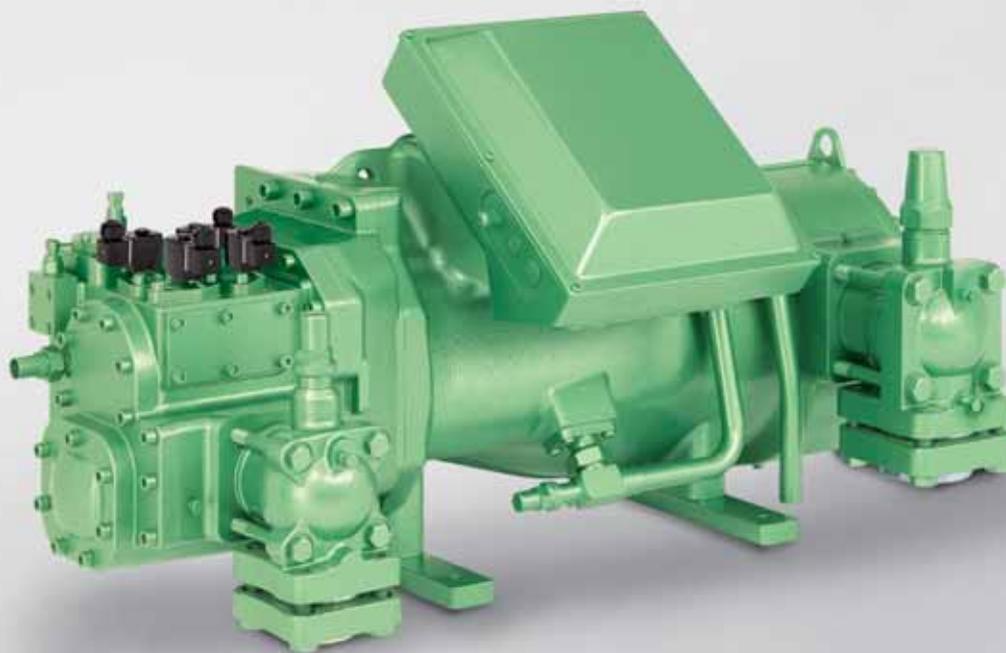
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