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IN THIS ISSUE:

- **Novel HP principles: Thermoelastic, Magnetic, Vuilleumier**
- **Reviews on Thermal Response Testing and Eco-Cute history**
- **Strategic Outlook: China**

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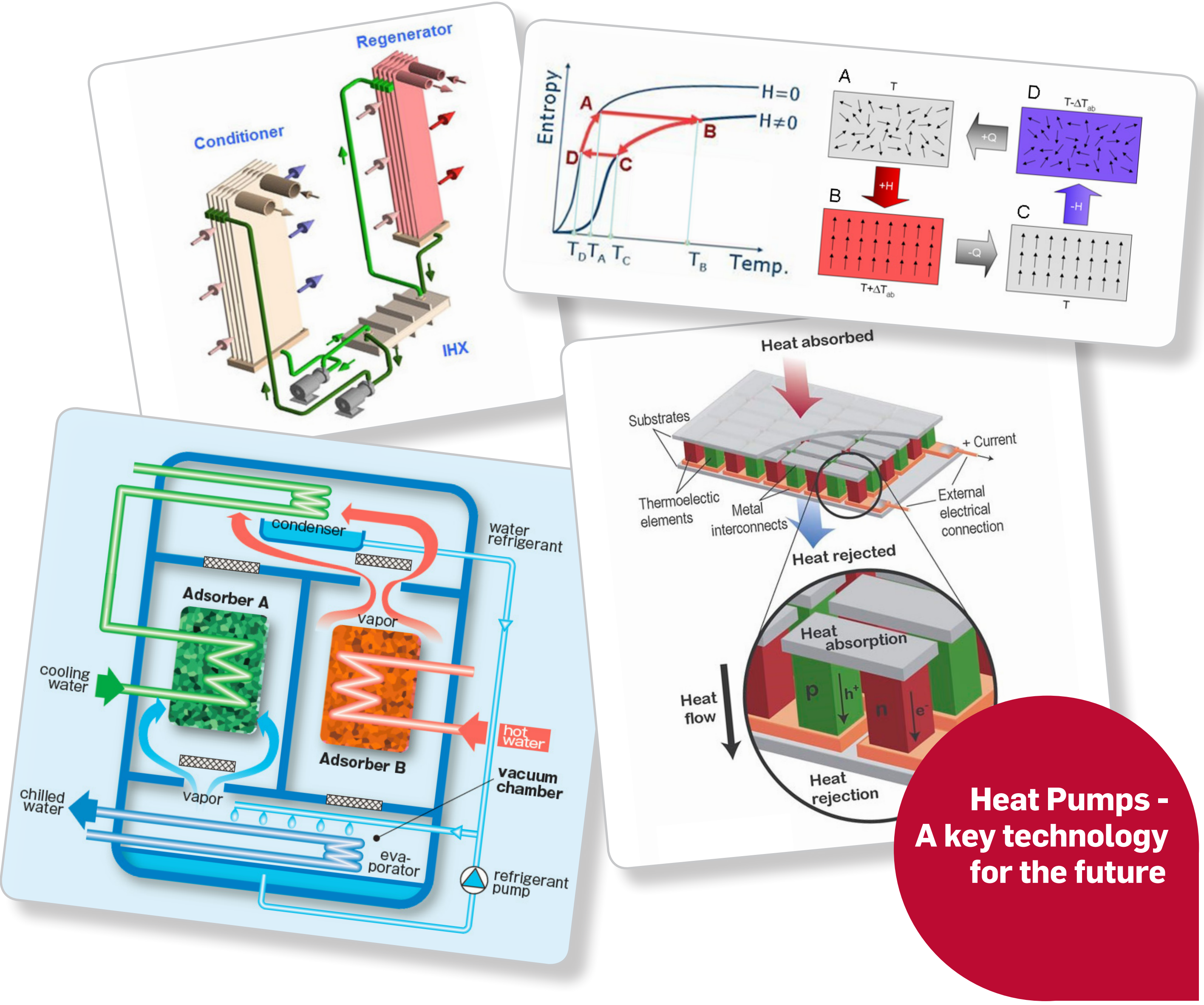
Innovative/alternative/non-conventional HP technologies



Heat Pumps - A key technology for the future

IEA **Heat Pump** CENTRE
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In this issue

Heat Pump Centre Newsletter, 4/2015
Vapor compression technology is a dominating technology for HVAC equipment, and has been so for a long time. However, the common refrigerants used generally have large values for Global Warming Potential, while alternative refrigerants generally have other drawbacks. Although significant work is being done to develop new refrigerants and refrigerant blends, another way forward is to use alternative heat pumping technologies.

The topic of this issue is **Innovative/alternative/non-conventional HP technologies**. The Foreword provides an introduction to the three topical articles, each focusing on one of the most promising of the new technologies. Of the two non-topical articles, one gives an overview of Thermal Response Testing for Ground Source Heat Pumps, while the other one reveals the early history of the Japanese Eco-Cute heat pump. We are also given a Strategic Outlook article from China.

Enjoy your reading!
Johan Berg, Editor

Heat pump news

Regulars

Topical articles

Topical articles

COLOPHON

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Foreword

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Building Technologies Program
USA

Non-Vapor-Compression HVAC Technologies

As this year comes to an end, we normally take time to reflect on our personal and professional accomplishments, and plan ahead to achieve greater success. The same thing can be said for heating, ventilation, and air-conditioning (HVAC) technologies. Vapor compression based systems have effectively and efficiently served the HVAC needs for residential and commercial buildings for close to 100 years. Vapor compression technologies are currently the dominant HVAC technology due to their scalability, relatively compact size, high reliability, and other attributes. However, HFC refrigerants commonly used in these systems today have detrimental global effects on the environment when released into the atmosphere. The scientific community has responded to such environmental threats by several proposals to phase down refrigerants with large global warming potential (GWP).

What is needed is a paradigm shift in HVAC technologies, moving beyond today's refrigerants and toward a future based (at least in part) on non-vapor-compression HVAC technologies with the ultimate goal to eliminate high GWP refrigerants altogether. This new paradigm is the ultimate environmental solution (zero GWP cooling fluids) for developed and developing countries. It will enable sustainable air-conditioning and heating solutions. At the same time we must understand that nearly all of the world's booming cities are in the tropics and will be home to an estimated one billion new consumers by 2025 [1]. Projections are that air-conditioning (A/C) use will increase worldwide. The challenge for us as a society is to develop new, improved A/C (and refrigeration and heating) technologies that are energy efficient and viable solutions for all.

What comes after vapor compression technology? U.S. Department of Energy has recently completed a report on the *Energy Savings Potential and RD&D Opportunities for Non-Vapor-Compression HVAC Technologies* [2] to help frame the state of these next generation technologies. Possible candidate technologies include, but are not limited to: sorption technologies, alternative thermodynamic cycles, solid state technologies, membrane technologies, electrochemical cycles, and mechanical technologies.

Promoting non-vapor compression HVAC research could lead to a significant transformation in the HVAC landscape and could make the world a better place for all people.

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1 *http://www.nytimes.com/2012/08/19/sunday-review/air-conditioning-is-an-environmental-quandary.html?pagewanted=all*

2 *http://energy.gov/eere/buildings/downloads/non-vapor-compression-hvac-technologies-report*

Column

Heat pump noise – a market barrier that needs more attention

Ola Gustafsson
Energy PhD-student
SP Technical Research Institute of Sweden
Sweden

Sound affects humans in both positive and negative ways. Sounds with positive effects can be sounds we subjectively define as pleasant or relaxing. Noise is often defined as unwanted sound, sound that is loud, annoying, unpleasant or unexpected. Noise affects people in everyday life and in different ways depending on the type of noise, noise level, frequency characteristic, time of day and variation over time. Two of the major environmental noise sources in our society are traffic and industrial processes. A less known noise source stems from appliances in the neighbourhood like air conditioning, ventilation, chimneys and residential heat pumps. However, many people have encountered heat pump noise related issues, either as customers trying to choose the best heat pump type for their house considering the noise related environmental impact, as heat pump owners being disturbed by noise when trying to sleep, or as neighbours sitting on their veranda irritated by a new heat pump on a nearby house. To summarize: disturbance caused by heat pump noise is a possible barrier for customer acceptance and further market growth.

The noise from a heat pump is created by several noise generating components. In an air source heat pump, the fan and the compressor (depending on the position of the compressor) are the main contributors to the noise. In other heat pump types, such as ground source heat pumps, the lack of a fan makes the compressor the dominating source. The noise level can be reduced by smart choices of components, clever positioning and the utilization of sound-absorbing environment and installations. A low noise energy-efficient fan together with an inverter-controlled compressor embedded in high quality insulation often results in a low noise product. But system aspects must be taken into account to reach really low noise and disturbance levels. Examples of such aspects are heat exchanger design and heat pump operation control.

Today, noise from heat pumps is normally described by their A-weighted sound power level, determined at one standard operating condition. However, the variation in sound power level is so large that a single measurement based on steady state operation is not at all representative of real-life operation. This is an even more significant issue for inverter controlled heat pumps, where the noise level easily can be manipulated with the current European test standard. In addition, there are other factors than the absolute sound power level that may influence the disturbance of noise, such as tonal components and transient behaviour of the noise. Just as with car emission and fuel consumption tests, a noise test method that fails to give a true picture of the product’s real behaviour may mislead customers when comparing different products. This could affect the heat pump market negatively in favour of other heating technologies.

During 2016, two PhD projects related to heat pump noise, performed at SP Technical Research Institute of Sweden and Chalmers University of Technology, will be finalized. The goal of the projects has been to identify heat pump related noise problems and to present noise reducing solutions. Also, in order to come closer to a solution with the misleading current test standard, SP has recently initiated a project together with several heat pump manufacturers. The aim of the project is to further identify what is considered disturbing in terms of heat pump noise, in order to be able to suggest a new noise evaluation method that better reflects the real operation of heat pumps. Also, the Austrian Institute of Technology (AIT) contributes to this field of research by performing very significant work and has just started the project “SilentAirHP” focusing on advanced noise battling (e.g. active noise cancelling) and measurement techniques to reduce the acoustic signature of current and next generation heat pumps.

We must not let heat pump noise be a barrier for market growth. Therefore, it is time to spend more research resources to reduce the noise level of heat pumps and to develop fair evaluation methods.

IEA HPT News

12th IEA Heat Pump Conference: Rethink Energy, Act NOW!

There are rapidly changing worldwide realities and changing insights into the feasibility of future energy infrastructures. The rethinking is that Heat Pumps are inevitable and give us affordable, reliable, sustainable and modern energy for all.

As heat pumps are available and as most of the buildings and infrastructures in 2050 are already existing or are built now it is of importance to act now. Heat pumping technologies play an important key role in a secure energy infrastructure. Buzz words are: energy security, integrated energy market; research, innovation and competitiveness; employment and new business models; energy poverty; energy efficiency; renewable energy.

The Heat Pump conference in 2017 will be held at Beurs-WTC Congress Center in the city centre of Rotterdam. From 1 January 2015 Beurs-WTC benefits from her own installation for renewable heating and cooling based upon heat pumping technologies and thus contributing to the reduction of CO_2 emissions.

The Rotterdam World Trade Center is heated with heat pumps

CALL FOR PAPERS

The Conference will consist of oral presentations and poster presentations. Invited keynote speakers will lead each major topic session. Papers for oral and poster presentations are being solicited with a general call for papers.

Abstracts (200 - 300 words) covering the themes of the Conference can be submitted on the website *www.hpc2017.org* from 1st December 2015 onwards until 31st March 2016. The abstracts will be screened and authors will contacted and be advised of acceptance by 30th June 2016. Full papers will be required by 30th November 2016.

The 12th IEA Heat Pump Conference starts on Monday starts with a series of Workshops and will, after the main plenary opening, session on Tuesday consist of three main bodies running in the parallel tracks:

- **Residential heat pumps**, focusing on topics such as: Energy Zero, Renovation, Hybrids, Domestic Hot Water, Multi Family Buildings.
- **Non residential heat pumps,** focusing on Industrial Heat Pumps, Waste Heat, Commercial Buildings, District Heating, Air Conditioning.
- **Innovation and R&D**, focusing on aspects like: ground sources, advanced storage systems, working fluids, combination with other renewable technologies, sorption technologies, non-vapour compression, smart grids/energy, cold climate heat pumps, air conditioning, gas driven heat pumps and combination with other renewable technologies.

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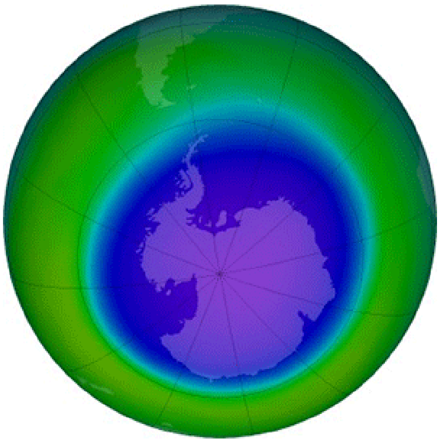
12th IEA HEAT PUMP CONFERENCE
2017 | ROTTERDAM

General

Ozone hole – one of the largest ever



Despite the phase-out of ozone-depleting refrigerants, the Antarctic ozone hole is currently among the largest ever observed. According to the World Meteorological Organisation (WMO), the ozone hole reached its maximum extent this year with an area of 28.2 million km² on October 2. However, the WMO stresses that this is due to colder than usual stratospheric meteorological conditions. Temperature conditions in the Antarctic stratosphere vary from year to year, it says, and does not indicate a reversal of the projected long-term recovery. Data from NASA, averaged over the 30 consecutive days, the ozone hole is 26.9 million km² – the third largest observed after the record-breaking ozone holes of 2000 and 2006.

"This shows us that the ozone hole problem is still with us and we need to remain vigilant. But there is no reason for undue alarm," said Geir Braathen, a senior scientist in WMO's Atmospheric and Environment Research Division.

Source: www.coolingpost.com

Policy

The world is set to use more energy for cooling than for heating

The world faces a looming and potentially calamitous "cold crunch", with demand for air conditioning and refrigeration growing so fast that it threatens to smash pledges and targets for global warming.

Worldwide power consumption for air conditioning alone is forecast to surge 33-fold by 2100 as developing world incomes rise and urbanisation advances. Already, the US uses as much electricity to keep buildings cool as the whole of Africa uses on everything; China and India are fast catching up. By mid-century people will use more energy for cooling than heating.

And since cold is still overwhelmingly produced by burning fossil fuels, emission targets agreed at next month's international climate summit in Paris risk being blown away as governments and scientists struggle with a cruel climate-change irony: cooling makes the planet hotter.

Source: www.eceee.org and www.theguardian.com

IEA calls for deeper institutional ties with China

On September 9, International Energy Agency (IEA) Executive Director Faith Birol called for a 'new era' of institutional ties between China and the IEA, one in which China participates fully in the Agency's work. Dr. Birol's call came during a visit to Beijing, his first official foreign trip since taking over as the leader of the IEA, on September 1.

Dr. Birol's visit to Beijing marked a break with IEA tradition. Instead of using his first official visit to travel to an IEA member country, he made China his first official destination, serving to highlight the importance of major developing nations to the international energy system.

Source: JARN, October 25, 2015

The Facebook data centre in northern Sweden. Photograph: David Levene for the Guardian, Source: www.theguardian.com

Source: *www.coolingpost.com*

Working fluids

World could agree on HFC phase-down in 2016

With HFCs now to be included within the Montreal Protocol, the meeting in Dubai in early November ended with real prospects of a global HFC phase-down agreement next year.

In the face of four amendments on the table from the Island Nations, India, the EU and North America, objections to forming an HFC contact group to begin negotiating an amendment were finally dropped.

US secretary of state John Kerry, in a US party of more than 20 led by Environmental Protection Agency administrator Gina McCarthy, hailed the negotiations as a major accomplishment that shows “that the world is ready for a new chapter in the fight against climate change.”

Source: www.coolingpost.com

Markets

GSHP tax incentives survey: incentives help, future visions differ

The results of a survey in the US on federal tax incentives for ground source heat pumps (GSHPs) have been summarized. There was a solid response from a variety of people working in the industry. GSHP manufacturers and system designers were the most represented groups among the 21 people who completed the survey.

The survey indicates that there is a consensus that tax incentives have helped boost the sales of GSHPs since they were put in place at the end of 2008. This is especially true for residential systems.

In terms of what motivates people to install GSHPS, performance/comfort, return on investment and federal tax incentives were identified as the most important factors.

Opinions as to what will happen if incentives are allowed to expire vary widely. Most everyone agreed that sales numbers would decline, but opinions varied as to whether the decline would be large or small.

Source: geoexanalytics.wordpress.com

China promotion policies for heat pump industry

According to the Ministry of Environmental protection, China’s central government has allocated CNY 26.3 billion (USD 4 billion) to prevent and control air pollution during the last three years. In addition to the financial input, air pollution classification has also been established and improved. With this policy support, the clean energy industry, such as the air-source heat pump industry, is ready for rapid development.

Source: JARN, October 25, 2015

Ongoing Annexes

IEA HPT Annex 40 Heat pump concepts for Nearly Zero Energy Buildings

IEA HPT Annex 40 investigates heat pump applications in buildings according to the future nearly zero energy requirements to be widely introduced in Europe after 2020 and in North America and Japan in the period between 2020 and 2030. The nine countries Canada, Finland, Germany, Japan, the Netherlands, Norway, Sweden, Switzerland, and the USA have participated in the 3 year Annex 40 project. Annex 40 is currently in the conclusion phase with the compilation of the national contributions to the Annex and the editing of the final report. Results are to be gathered by the end of 2015.

Annex 40 Tasks are dedicated to the state-of-the-art in Task 1, a concept assessment in Task 2, technology developments and field monitoring in Task 3 and the integration of nZEB with heat pumps into the energy system in Task 4.

Regarding the state of nZEB definitions, 15 European countries have a definition in place, while in the other countries a definition is still under development. A common rating procedure has been developed by CEN and REHVA in order to harmonise different definitions.

Regarding realised nZEB, most buildings are smaller residential buildings. A majority of the concept are so-called “all electric buildings” equipped with a heat pump and PV system in order to meet the nearly zero energy balance. Heat pumps already have large shares regarding the installed building systems in nZEB.

In Task 2, case studies of building systems for nZEB have been performed. Despite different boundary conditions in central Europe and Nordic countries, the case studies yield results showing that heat pumps are among the most energy-efficient and cost-effective systems for nZEB applications. Moreover, under Swedish and Finnish market conditions, ground source heat pumps are a viable solution despite the low space heating demand. A Japanese case study confirms that nZEB in office applications can be reached with efficient appliances and lighting systems by choosing an efficient heat pump for space heating and cooling. In Canada, viable heat pump solutions depend on the market conditions, since in the Eastern part of the country, ground-source and cold climate air source heat pumps are economic solutions, while in the western part, the systems cannot compete with gas heating at current market conditions.

Task 3 is dedicated to different prototype technology developments. In the USA, different variants of an integrated heat pump, among others a gas-engine driven unit, have been developed, while in Canada and Switzerland, the integration of the heat pump and solar collectors, partly with ice storage, has been lab-tested and simulated. At NIST, a Residential Testing Facility for NZE technologies (NZERTF) has been installed and operated for two years. Regarding field monitoring, some of the first Nordic nZEBs have been monitored and evaluated in Norway.

In Task 4, the integration of nZEB into the energy system is considered. In Switzerland, two nZEBs with residential and office use have been evaluated regarding load management options including the heat pump and electro-mobility. An increase of the self-consumption of on-site PV generated electricity of about 15 % could be achieved. In Germany, load management options for office buildings equipped with TABS are investigated. Simulation results show that a shift of the heat pump operation from night time to daytime hours can enhance load and supply cover factor by about 10 %.

Results of Annex 40 have been presented in the frame of the 4th European Heat Pump Summit 2015 on October, 20-21 in Nuremberg. Final reports are expected to be published in spring 2016.

Information and workshop publications of Annex 40 can be found on the website http://www.annex40.net.

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IEA HPT Annex 41 Cold Climate Heat Pumps (CCHP)

In the past quarter the Annex 41 Participants continued to make progress on their Country projects.

The 4th working meeting has been scheduled for January 22, 2016 in Orlando, FL, USA, just before the start of the 2016 ASHRAE Winter Conference.

Three papers from the US Annex 41 team are scheduled to be presented in a Conference paper session on January 26 at the ASHRAE meeting.

A paper from the Austrian team has been accepted for presentation at the St. Louis ASHRAE meeting in June 2016.

The Annex final report is planned to be submitted to the ExCo around July 2016 according to the target schedule in the table below as established at the May 2015 meeting in Vienna.

The Annex web site is http://web.ornl.gov/sci/ees/etsd/btric/usnt/QiQmAnnex/indexAnnex41.shtml

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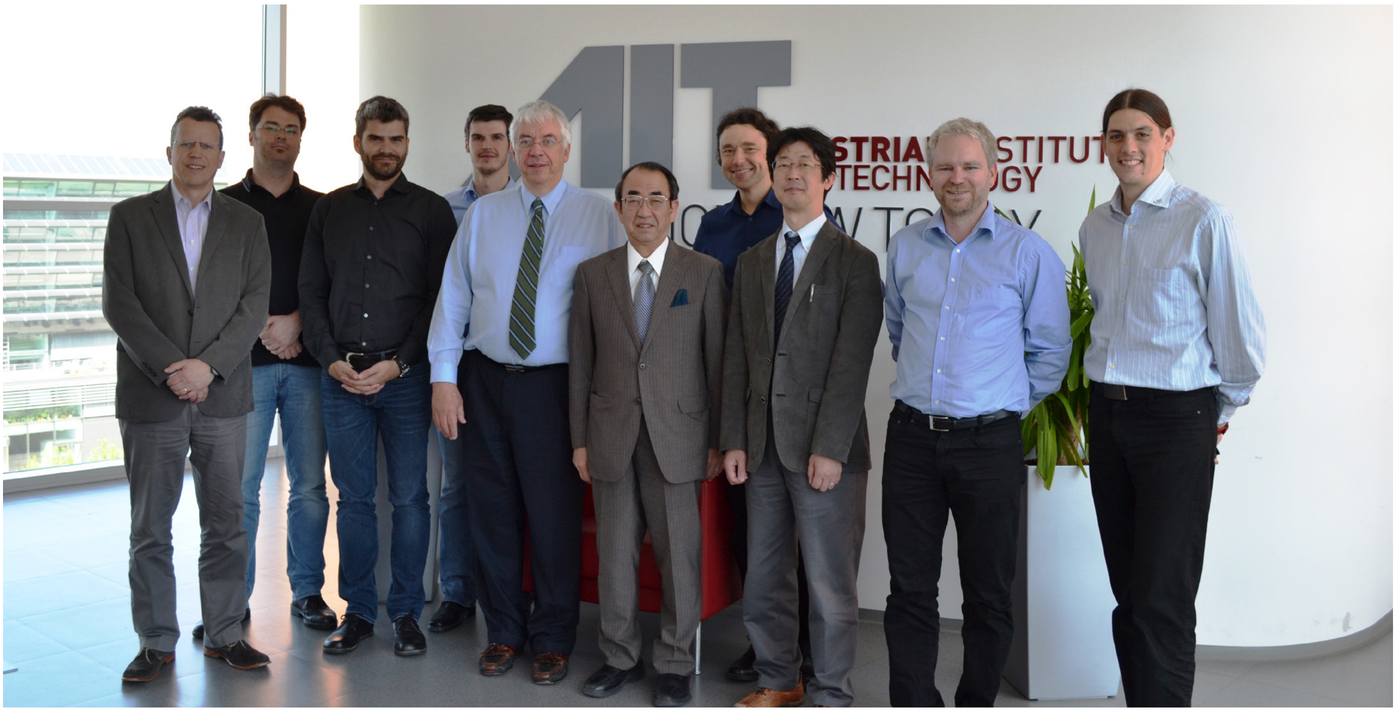

Annex 41: Group photo of Annex 41 members - May 8, 2015, Vienna, Austria

Table: Annex 41 – Final Report schedule

Target Date	Responsible Group	Action Item or Activity
15 April 2016	Each Annex Participant	Participants forward draft final country reports to OA
1 June 2016	Operating Agent	OA compiles draft final report & forwards to participants for review
1 July 2016	Each Annex Participant	Participants return comments on final report draft to OA
31 July 2016	Operating Agent	OA finalizes Annex report and forwards to ExCo and Heat Pump Centre for review/approval

IEA HPT Annex 43 Fuel-driven sorption heat pumps

Participating countries:
Germany (operating agent), Austria, France, Italy, South Korea, United Kingdom, USA.

Fuel driven sorption heat pumps have recently gained more and more attention, from both a research and a market perspective. At least two more companies are expected to offer products in 2016. Customers, planners and installers still do not seem well informed, and more work needs to be done to prove that this type of heat pump might play a significant role in future energy systems.

Objectives

The scope of the work under this annex covers the use of fuel driven sorption heat pumps in domestic and small commercial or industrial buildings and applications. Additionally, the possibility of supplying cooling may be considered, where applicable. The main goal is to extend the use of fuel driven heat pumps by accelerating technical development and market readiness for this technology, as well as to identify market barriers and supporting measures.

Work performed and current status

In September 2015, an international conference on sorption heat pumps with more than 100 participants from all over the word was organised by Annex 43 members in Milazzo, Sicily, Italy. The topics ranged from new working pairs for gas driven heat pumps, over recent component development, to field test results. One highlight was the session "Systems and applications", where four companies gave an inside view of their plans with regard to gas driven heat pumps. More information can be found at *www.sorptionfriends.org*.

Furthermore, a full session on gas driven heat pumps was given by Annex 43 members at the "European heat pump summit 2015" held on 20 October in Nuremberg. The state of the art of this technology was presented before some 200 experts in the heat pumping business. The latest news on performance evaluations, field test results and market expectations was also presented.

Annex 43: Annex 43 members at the last meeting in Vienna, Austria

In the coming months, a round robin test of a gas driven adsorption heat pump is planned involving four labs across Europe with a view to comparing different measurement procedures, e.g. EN 12309 and VDI 4650-2, and the usefulness of calculating SPFs based on these measurements as compared to field test data.

The next Annex 43 meeting is planned to take place on 9 and 10 December in Wernau, Stuttgart, and will be hosted by Bosch.

More information about the annex can be found at:
https://www.annex43.org/

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IEA HPT Annex 44 Performance indicators for energy-efficient supermarket buildings

Denmark has now officially joined Annex 44, reinforcing the teams from Sweden and The Netherlands.

From the Danish side, work on the Annex will primarily be performed by the DTI, with strong support from the Danish industry (Danfoss).

The teams from Sweden, Denmark and the Netherlands have met in August in Yokohama (Japan) at the International Congress of Refrigeration, and more recently (October 29th, 2015) at an Annex working meeting in Stockholm, Sweden. At this last meeting, Denmark announced that it could contribute significantly to the database on supermarket energy consumption values, with data on 500 Danish supermarkets. Most of this data is not detailed, beyond the main characteristics, but for 100 supermarkets more detailed data is available.

Also new data from The Netherlands will become available, covering the same supermarkets as analysed before, but with new energy consumption data for the year 2014.

The new data from Denmark and the Netherlands, as well as data from a selected number of Swedish supermarkets, will be used in the first instance to substantiate (or contradict) the primarily findings of the Annex work performed so far. These are that conventional technical parameters alone cannot sufficiently explain the practical yearly energy consumption of a supermarket. “Non-conventional” technical parameters such as system dynamics, and non-technical parameters such as management focus, probably play an important role in the overall energy consumption.

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Ongoing Annexes

Bold text indicates Operating Agent.

Annex 37 Demonstration of Field measurements of Heat Pump Systems in Buildings – Good examples with modern technology	37	CH, NO, **SE**, UK
Annex 39 A Common method for Testing and Rating of Residential HP and AC Annual/Seasonal Performance	39	AT, CH, DE, FI, FR, JP, KR, NL, **SE**, US
Annex 40 Heat Pump Concepts for Nearly Zero-Energy Buildings	40	CA, **CH**, DE, FI, JP, NL, NO, SE, US
Annex 41 Cold Climate Heat Pumps (Improving Low Ambient Temperature Performance of Air-Source Heat Pumps)	41	AT, CA, JP, **US**
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Annex 43 Fuel Driven Sorption Heat Pumps	43	AT, **DE**, FR, IT, UK, US
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IEA Heat Pumping Technologies participating countries: Austria (AT), Belgium (BE), Canada (CA), Denmark (DK), Finland (FI), France (FR), Germany (DE), Italy (IT), Japan (JP), the Netherlands (NL), Norway (NO), South Korea (KR), Sweden (SE), Switzerland (CH), the United Kingdom (UK), and the United States (US).
All countries are members of the IEA Heat Pump Centre (HPC). Sweden is the host country for the Heat Pump Centre.

Strategic Outlook of Heat Pump Development in China

Cooper Hengyi Zhao, China

At present, China is transforming its economy to a more sustainable development approach, and making significant efforts to cut CO_2 emissions and fossil energy consumption. Heat pumps, as an energy saving and renewable energy technology, have achieved good growth in recent years. But, further market development needs policy support, like listing air source heat pumps as a renewable energy technology, and to set unified energy efficiency standards and labelling for all kinds of boilers. The China Heat Pump Alliance and International Copper Association are both actively facilitating industry development.

Current market situation

Air to air heat pumps are widely used in China. Annual domestic sales of reversible air to air room air conditioners (RAC) is around 40 to 50 million units. Around 90 % of RAC sold in China are reversible with a cooling and heating function. The average heating operation time for each room air conditioner in China is around 300 hours. Compare this to a cooling operation time of around 1000 hours and RAC is mainly a cooling application. VRF (Variable Refrigerant Flow) air to air heat pumps are also growing fast in China. Annual sales increased from 1 034 919 units in 2013 to 1 242 500 units in 2014.

Air to water heat pumps include air to water reversible air conditioning and air source heat pump water heaters. Annual domestic sales for air to water air conditioning is around 6 billion CNY (close to 1 billion USD; 1 CNY≈0.16 USD), these mostly use screw and scroll compressors and are installed in commercial buildings.

Air source heat pump water heaters (AHPWH) have seen rapid growth in China over the past 5 years. The compound annual growth rate is more than 25 %. The domestic sales in China of AHPWH (see table 1) reached 6.3 billion CNY, and 1 211 000 units in 2014. Compared to 2013, the annual growth rate is 26.3 % for the domestic market, and 0.9 % for the export market. The main growth comes from the domestic market. The air source heat pump market associated with floor heating and radiators for space heating was even smaller at 15 000 units in 2014 where wall-mounted gas boilers dominated with 1 640 000 units.

Table 1. The domestic sales in China of Air source heat pump water heaters (billion CNY) during 2013 and 2014 [Data source: China Heat Pump Alliance]

	China AHPWH Domestic sales (billion CNY)		
2013	4.98	Household	843 000 Units
		Commercial	90 000 Units
2014	6.35	Household	1 106 000 Units
		Commercial	105 000 Units

Table 2. Sales data of Water source heat pump in 2013 and 2014 [Data source: China Refrigeration and Air Conditioning Industry Association (CRAA)]

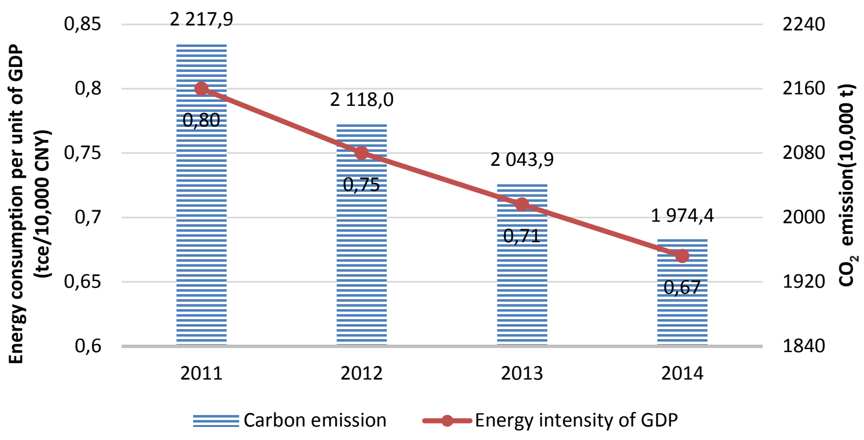
Product	2013 Sales (Units)	2014 Sales (Units)
Water source heat pump, (water to air)	63 470	55 960
Water source heat pump, (water to water)	25 892	24 080

Ground/water source heat pumps, GSHP, in China are mainly used in commercial buildings and have also developed rapidly since 2001 in cold regions with strong support from central and local government. However, the growth rate slowed considerably after 2011, and even began to decrease after 2013. According to the China Refrigeration and Air Conditioning Industry Association (CRAA), water source heat pump sales data in 2013 and 2014 is as table 2 above.

Energy conservation and consumer incentive

2015 is the final year of China's national 12th Five-Year plan outline, in which, energy consumption per unit of GDP is set to fall by 16 % (based on 2010 levels) by 2015 and the reduction in carbon intensity of GDP is set to fall by 17 %. Over the past four years, the use of energy per unit of Gross Domestic Product (GDP) has fallen as expected and carbon emissions have also dropped, as shown in Figure 1.

The National Development and Reform Commission (NDRC) is generally leading national energy saving and environment protection affairs in China. In order to facilitate energy saving product market growth, NDRC started the “Energy saving production market subsidy scheme” in 2012. AHPWH was included in the scheme from June 1, 2012 to May 31, 2013. AHPWH buyers who were eligible could receive subsidies from 300 to 600 CNY (around 10 % of the total retail price) depending on the rated heating capacity and COP, see table 3.



tce = tonnes of coal equivalents

Figure 1. Energy intensity of GDP and carbon emission in China [Data source: National Bureau of Statistics of China. GDP used to calculate the energy intensity is based on the 2014 price level. 1 EUR=8.2 CNY, 1 USD=6.2 CNY approximately in 2014].

Table 3. Subsidy to air source heat pump water heater

COP	Rated heating capacity (W)	Subsidy (CNY)
3.4 ≤ COP < 4.0	≤ 4500	300
	> 4500	350
COP ≥ 4.0	≤ 4500	500
	> 4500	550

Air pollution control

Coal fired boilers for space heating are a key reason for air pollution, especially in the north of China. In the Air Pollution Prevention and Control Action Plan introduced by the State Council in September 2013, heat pump application is recommended as an energy saving and clean energy space heating product to replace coal fired boilers.

The Beijing-Tianjin-Hebei (BTH) region and surrounding areas will continue to intensify efforts to cut coal fired boilers over the next five years. Most of the areas without a district heating supply facility are located in suburbs of cities or rural areas and where it is unlikely that the gas distribution network will reach in the next few years. There will be a big electricity driven heating product market. In 2015, Beijing municipal government gives a subsidy of up to 30 000 CNY per household to families who use clean energy products, like heat pumps, to replace coal fired boilers. The policy is expected to last for a two year period.

Renewable policy

Since 2009 geothermal has been defined as renewable energy in Chinese renewable legislation. Being a renewable energy product, a subsidy from central and local government is available for GSHP. For example, in 2009, the GSHP application in rural areas could receive a subsidy of 60 CNY per m^2 from central government. In Beijing, GSHP could receive a 50 CNY subsidy per m^2 from local government. However, most of these government subsidies were stopped in 2012.

Aerothermal and ASHP so far have not been incorporated in the renewable energy product list in Chinese national legislation and regulations. However, several provincial governments already recognize it as renewable energy, for example, Zhejiang province, through local legislation, aerothermal has been approved as renewable energy since 2012. In 2015, Fujian, Hebei, Shandong and Beijing also published local regulations which accepted ASHP as a renewable energy product. The national level policy is under evaluation.

Energy efficiency standards and labelling

In China, the domestic water heater market is around 30 to 40 million units per year. Nevertheless, electrical resistance water heaters still hold the largest market share, around 40 % by unit, followed by demand gas and solar thermal water heaters (see figure 2). Despite the rapid market growth of AHPWH over the past five years, it only occupied around a 3 % market share by unit in 2014.

One major obstacle is that current energy efficiency labels use

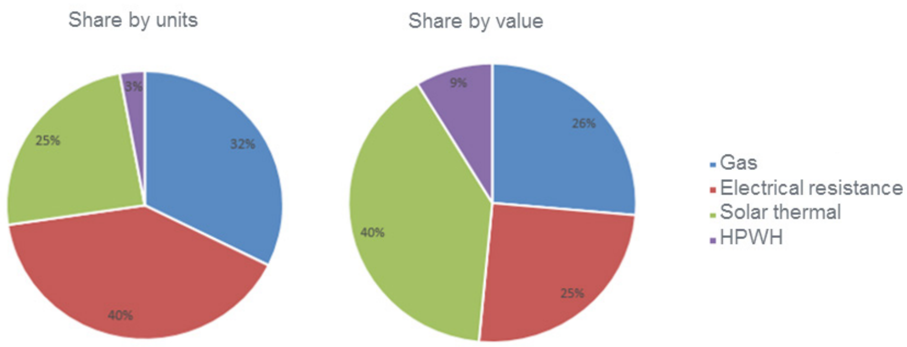
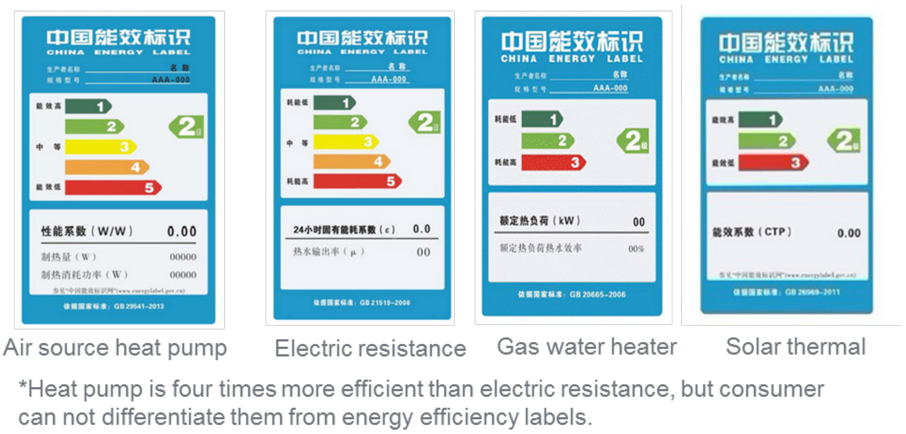


Figure 2. 2014 China residential water heater market share [Data source: China Heat Pump Alliance]



*Heat pump is four times more efficient than electric resistance, but consumer can not differentiate them from energy efficiency labels.

Figure 3. Chinese energy efficiency labels for four kinds of water heaters

different evaluation methods for all four kinds of water heaters (see figure 3). Normal consumers cannot differentiate which one is more energy efficient through these labels. A united evaluation standard for all kinds of water heating equipment is needed on this market and would be beneficial for AHPWH.

China Heat Pump Alliance

The China Heat Pump Alliance, CHPA, nowadays is the most important organization for the Chinese heat pump industry. CHPA was initiated by the China Energy Conservation Association (CECA) and the International Copper Association (ICA). The organization aims to facilitate the market growth of heat pumps, especially the air source heat pump water heating equipment, in China.

CHPA spoke for the industry during the central and local government policy and regulation making process, and set up a platform for technology and market information communication. CHPA has already entered into cooperation agreements with international partners, like Heat Pump and Thermal Storage Technology Center of Japan (HPTCJ), European Heat Pump Association (EHPA), and has fruitful cooperation with the IEA HPC.

Conclusion

Although the Chinese economy growth rate is slowing down, and the building and construction sector is entering a difficult phase, the environment protection and energy conservation industry is expected to grow fast in the coming years, with strong policy and financial support from the government.

The question for the heat pump industry is how to make "heat pumps" a priority choice for policy makers to achieve energy saving and air pollution control targets, and how to make more consumers accept a "heat pump" as a main heat source for domestic hot water and space heating.

We expect the Chinese heat pump industry, especially air source heat pumps, to grow rapidly over the next 5 to 10 years. The growth rate will be more than double that of the GDP growth rate.

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An overview of thermoelastic cooling technology

Suxin Qian, Yunho Hwang, Reinhard Radermacher, Ichiro Takeuchi, USA*

Recently, the concept of achieving cooling by squeezing a solid-state shape memory alloy has attracted people's attention since it is a new technology and does not rely on any fluorinated fluids. Thermoelastic cooling has demonstrated its potential for cooling based on its superior latent heat to other competitive not-in-kind cooling technologies. After five years of research, we proved the concept of thermoelastic cooling and have improved its performance as a technically viable and environmentally friendly cooling option although it is still in early research and development stage. With more research efforts to be carried out in the future, this brand new cooling technology could be used in our homes and offices.

Introduction

Thermoelastic cooling, also known as elastocaloric cooling, is one of the not-in-kind technologies to pump heat from a low temperature heat source to a high temperature heat sink, by utilizing the martensite-austenite phase transformation found in shape memory alloys (SMAs) [1]. The exothermic phase change occurs upon stress, which may be induced by tension, compression or torsion. Cooling is achieved during the reverse phase change process when the stress is removed. The typical latent heat of the martensitic phase transformation is 12 J·g^{-1} for Ni-Ti alloy, which is a state-of-the-art SMA. A 24 K temperature increase was measured upon adiabatic loading, and reversely a 17 K temperature drop was observed during the unloading process [2]. This latent heat is equal to 78 MJ·m^{-3} volumetric energy density, which is in the same order of magnitude with that of a conventional refrigerant, i.e. 215 MJ·m^{-3} for R134a under 25 °C room temperature. A comprehensive and systematic review indicated that thermoelastic cooling is the most promising not-in-kind cooling technology among 17 candidates [3].

Cycles

SMA needs to undergo specific cycles in order to produce a useful and continuous cooling or heating. The Brayton cycle, one of the viable single-stage cycles, is illustrated in Fig. 1. This cycle has been extensively used and validated by dynamic modelling and prototype testing [1]. At least two identical beds containing SMA are needed to achieve the heat recovery (HR) feature. The first and second beds start at state 1 and 4, respectively, with a half cycle delay. When subject to the loading force adiabatically, bed 1 transforms from austenite to martensite, releases latent heat and increases its temperature to state 2. The intermediate state 1′ on the stress-strain diagram in Fig. 1 represents the threshold when the phase change initiates. Meanwhile, the temperature of bed 2 drops to state 5 by releasing the force. The first stream of heat transfer fluid (HTF) carries the heat from bed 1 to a heat sink at temperature of T_h, resulting in the temperature drop from state 2 to state 3 for bed 1. Cooling is delivered to a heat source (T_c) by a second HTF, corresponding to the temperature increase from state 5 to state 6 for bed 2. After the two beds approach T_h and T_c, respectively, the HR process circulates a third HTF

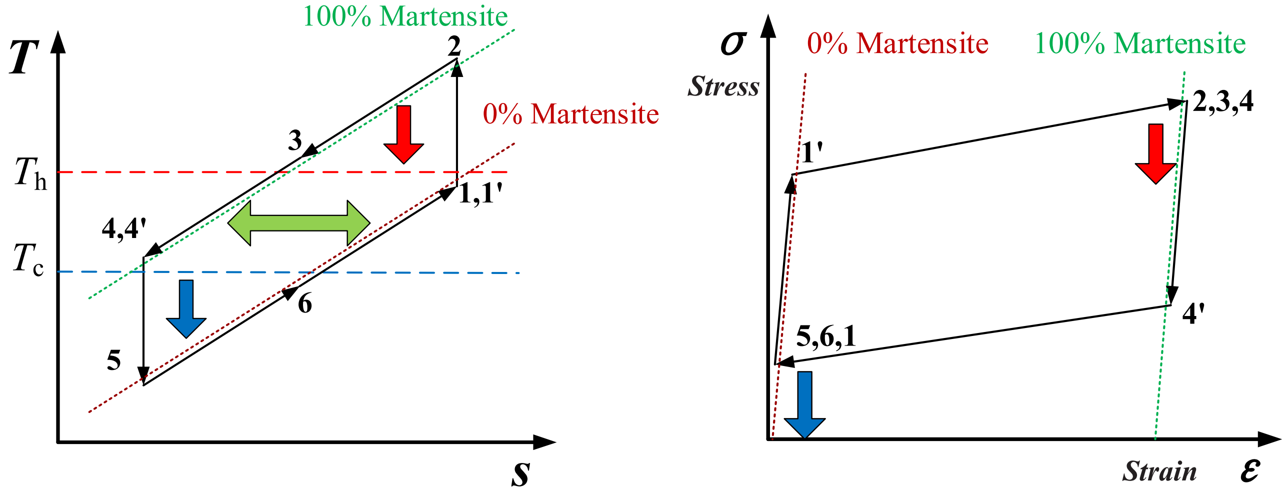

Figure 1. Single-stage reverse Brayton cycle for thermoelastic cooling using SMAs [1]

internally between the two SMA beds, to further cool bed 1 by using the heat from bed 2, and vice versa. Following an analogy from the conventional counter-flow heat exchanger, the proposed "counter-flow in time scale" HR process can achieve 60 ~ 80 % efficiency when the HR duration and thermal mass of the regenerator HTF are optimized properly [4]. Both heat transfer and HR in a cycle needs a few seconds, resulting in a total cycling frequency to be 0.05 ~ 0.1 Hz.

Another viable cycle can be achieved by combining the heat transfer and HR processes together by using a cascaded configuration, as shown in Fig. 2 [5]. In the cascade cycle design, HTF is pumped right after loading of the SMAs to reject heat. The reverse flow delivers cooling to the heat source after the unloading process. This design couples the HR with heat transfer, reducing the cycle duration, and is capable of operating under 0.1 ~ 2 Hz frequency. Nevertheless, since it is based on a cascaded design, the potential coefficient of performance (COP) may be less than that of the single stage cycle shown in Fig. 1.

Prototypes

There are a few published experimental researches based on this technology [5-7]. The first compression based prototype using Ni-Ti tubes as functioning material has been designed, developed and tested [6] as shown in Fig. 3. The prototype was based on the single stage cycle shown in Fig. 1. Water was used as HTF in the prototype to reject heat to a heat sink, transfer cooling to the heat source, and conduct HR. The maximum cooling capacity achieved was 65 W. The maximum system temperature, measured by the water temperature difference between the heat sink and source, was 4.2 K. This prototype proved that the cycle proposed in Fig. 1 was technically viable. The system can be easily scaled up by simply adding more Ni-Ti tubes and increasing HTF pump and driver size.

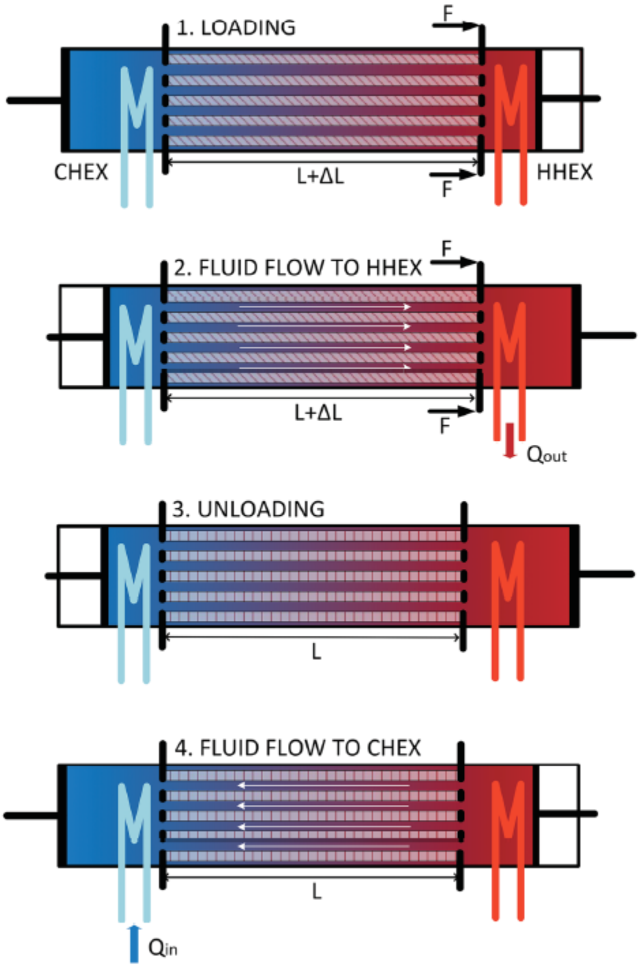

Figure 2. Cascaded configuration as an active elastocaloric regenerator for thermoelastic cooling [5]

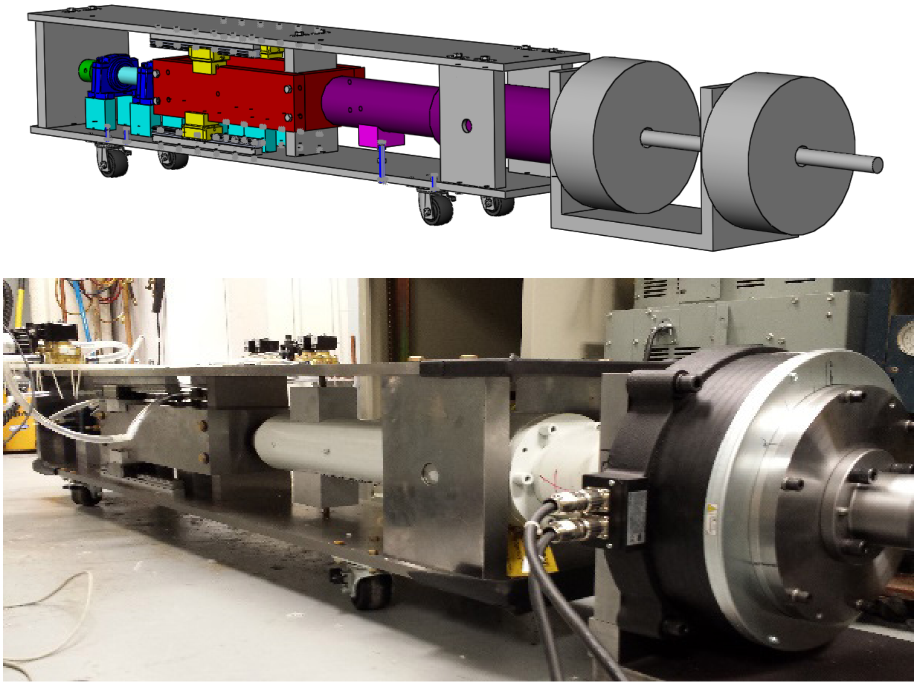

Figure 3. World first compressive thermoelastic cooling prototype based on Ni-Ti tubes [6]

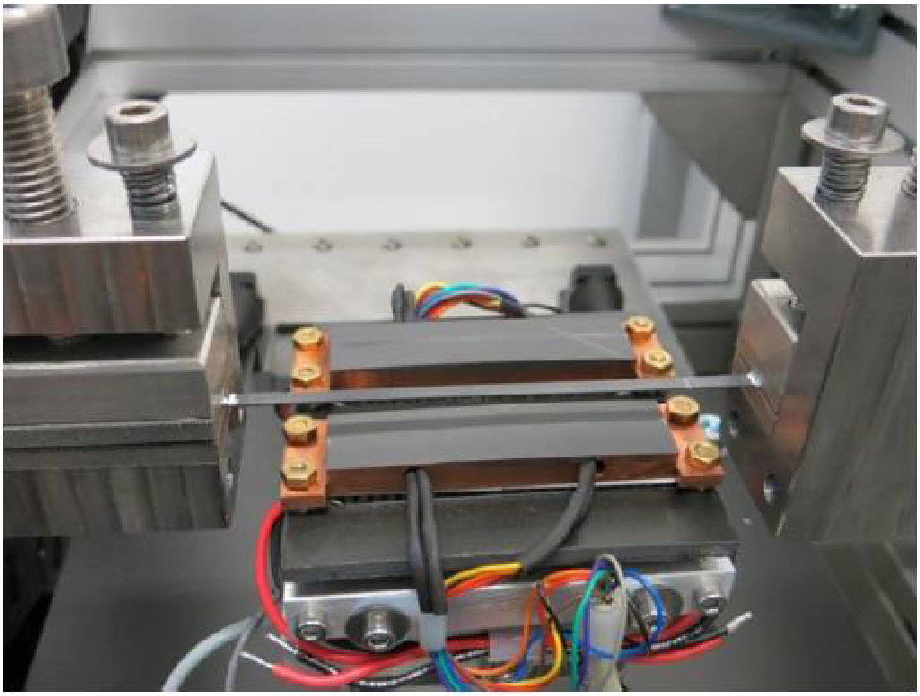

Figure 4. Demonstrator of thermoelastic cooling based on Ni-Ti plate [7]

In Fig. 4, a well-designed demonstrator of this cooling technology was developed using Ni-Ti plate [7]. Tension instead of compression was applied in the system. No HTF was used due to its small size, wherein two metals with large thermal mass were used as heat sink and heat sources. An additional motor was used to control the cyclic contact between the Ni-Ti plate and heat sink/source. A similar single-stage cycle was used without HR due to lack of HTF. The maximum system temperature lift measured by the solid-state heat sink/source was 7 K.

Another neat demonstrator was developed based on Ni-Ti plate as well [8]. Indirect tension was a result of adjusting the position of the spacer in the middle of Fig. 5. In one of the designs [8], air was used as HTF on the heat sink side, and a metal plate was used as the heat source. The authors concluded that air was not a good HTF due to a large heat transfer time constant between the Ni-Ti plate and the air. In the second design [8], both heat sink and heat source were metal plates, wherein 7 K temperature lift was achieved.

System Performance

The performance of a thermoelastic cooling/heat pump system can be evaluated by three quantities, i.e. temperature lift, cooling/heating capacity, and COP. The temperature lift has been reported by the experimental studies in the past, ranging up to 7 K [6-8]. For a realistic water chiller to provide cooling for air-conditioning, at least 20 K temperature lift is required according to AHRI 550/590 standard. This temperature lift can be even larger for heat pump application. So far, none of any prototype can provide such a large temperature lift to measure cooling/heating capacity and COP. On the other hand, with less influence of system design challenges, numerical models can provide useful information about potential system performance. Up to 0.38 $W \cdot g_{Ni\text{-}Ti}^{-1}$ cooling capacity, or 0.53 $W \cdot g_{Ni\text{-}Ti}^{-1}$ heating capacity was reported by a system dynamic model under 10 K temperature lift [1]. It was also reported that the baseline system COP could be 1.7 when considering all the losses. Despite the fact that the assumed 70 % mechanical driver's efficiency and additional pump power consumption cannot be reduced significantly under current state-of-the-art, other losses could be reduced. The most significant loss is a result of the SMA's irreversibility during the martensitic phase transformation, which could be reduced by engineering SMAs with less hysteresis [9]. The loss can be further reduced by replacing the Brayton cycle introduced earlier by a hybrid cycle to approach isothermal compression. Heat transfer and heat recovery can be enhanced by optimizing the operating conditions, including flow rates and cycling frequency. The impact of system dead thermal mass can be reduced by better component design and HTF selection. Overall, with the hybrid cycle, optimum heat transfer and heat recovery, and less dead thermal mass, the system

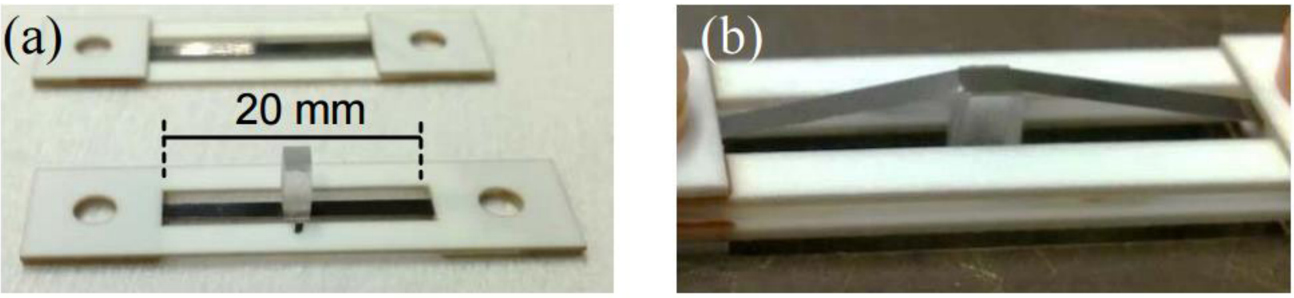

Figure 5. Demonstrator of thermoelastic cooling based on Ni-Ti plate [8].

COP could reach 7.7 by assuming the same mechanical driver's efficiency and pump power consumption under 10 K temperature lift [1].

The system performance can be further enhanced by using novel designs [10]. A larger surface to volume ratio for SMA guarantees a faster heat transfer and heat recovery. Less dead thermal mass of HTF inside the SMA beds reduces the ratio between active thermal mass of SMA and the overall system dead thermal mass, which helps eliminate the system cyclic loss caused by periodically heating and cooling the parasitic parts with dead thermal mass. Consequently, the "tube-in-tube" design was proposed to achieve these goals. Another design inserting the plastic tube to insulate the heat loss from HTF entering and exiting the SMA beds to the metal parts was also helpful to enhance the system performance. The system temperature lift can be enhanced to 27.8 K with these novel designs for a single-stage Brayton cycle, corresponding to system COP of 4.1 with optimum operating parameters [10]. Another approach was to use the cascaded regenerator design [5]. With 30 K system temperature lift, the maximum system COP can be around 5 without considering the mechanical driver's efficiency and pump power consumptions. By using the cascaded regenerator design, the system operating frequency can be increased to around 1 Hz, resulting in up to 7 $W \cdot g_{Ni\text{-}Ti}^{-1}$ specific cooling capacity.

Challenges and Prospects

While all of the prototypes developed so far have faced numerous challenges, only a few of them were addressed at this stage. Some of the universal challenges that need to be addressed in future studies are as follows:

- Material with large latent heat and good fatigue life
- Optimized loading/unloading rate
- Highly efficient heat transfer and heat recovery/regeneration
- Minimized friction
- Drivers capable of providing large force and small displacement

Nevertheless, the concept of thermoelastic cooling has been proved by a few different technical viable approaches. The new materials development is on the way [11]. More research work is now being carried out globally to improve the performance of this promising not-in-kind cooling technology.

Conclusions

Thermoelastic cooling is a promising novel not-in-kind cooling technology. Due to the superior latent heat in SMAs, thermoelastic cooling appears to be more promising than other solid-state cooling technologies. Both single-stage cycle and cascaded regenerator cycle can be applied to this technology. The single-stage cycle has already been proved to be functional by several prototypes. Although the current prototypes can only provide a lower than 10 K temperature lift, the performance is expected to be enhanced significantly by future studies in a few years.

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Modernizing the Vuilleumier Cycle: Recent developments for a novel natural gas air-conditioner and heat pump

Seann Convey and Paul Schwartz, USA

Thermally driven heat pumps can offer dramatic savings by extracting renewable heat energy from any environment, including cold climates. Current HVAC systems face operational limitations including low efficiencies and reliance on the strained electric grid which may result in significant energy costs and emissions. The Vuilleumier cycle has demonstrated proven advantages including efficiencies that exceed state-of-the-art systems, without the use of harmful refrigerants. Recently a startup company, ThermoLift, has received international support and funding from the U.S. Department of Energy and New York State Energy Research and Development Authority for the commercialization of an innovative modernized Vuilleumier device for residential and light commercial heating, cooling, and production of hot water in a single appliance.

Introduction

Renewable energy is the cornerstone of our planet's ever-expanding energy demands. That includes thermally-driven heat pump systems – the European Union has classified heat pumps as renewable sources of energy – and a new innovation to the Vuilleumier Cycle thermal heat pump.

Fossil fuels provide the majority of global electricity and are therefore the "primary energy" powering electric heat pumps. However, electrical production routinely delivers only 35 % of the primary energy consumed for its production. If a high-efficiency solution could harness the thermal energy in natural gas, it could power a heat pump with a high COP for both heating and cooling – an entirely new category of HVAC.

The Vuilleumier heat pump represents a potential new category of equipment: a single device capable of heating and cooling air and heating water, with global applications across the commercial, residential and industrial sectors. The Vuilleumier cycle's high COP potentially represents the lowest carbon footprint and highest energy output per unit of primary energy, of all categories of heat pumps.

State-of-the-Art Heating and Cooling Systems

Air conditioning, space heating and water heating typically comprise the largest proportion of energy use and expenditure in the U.S. and Europe, accounting for nearly 20 % of total energy consumed annually. Improved efficiency in HVAC and hot water (HW) systems present a tremendous opportunity for energy and cost savings, as well as significant reductions in greenhouse gas emissions. However, current HVAC and HW systems are restricted in the benefits they provide and high-efficiency models are often very expensive.

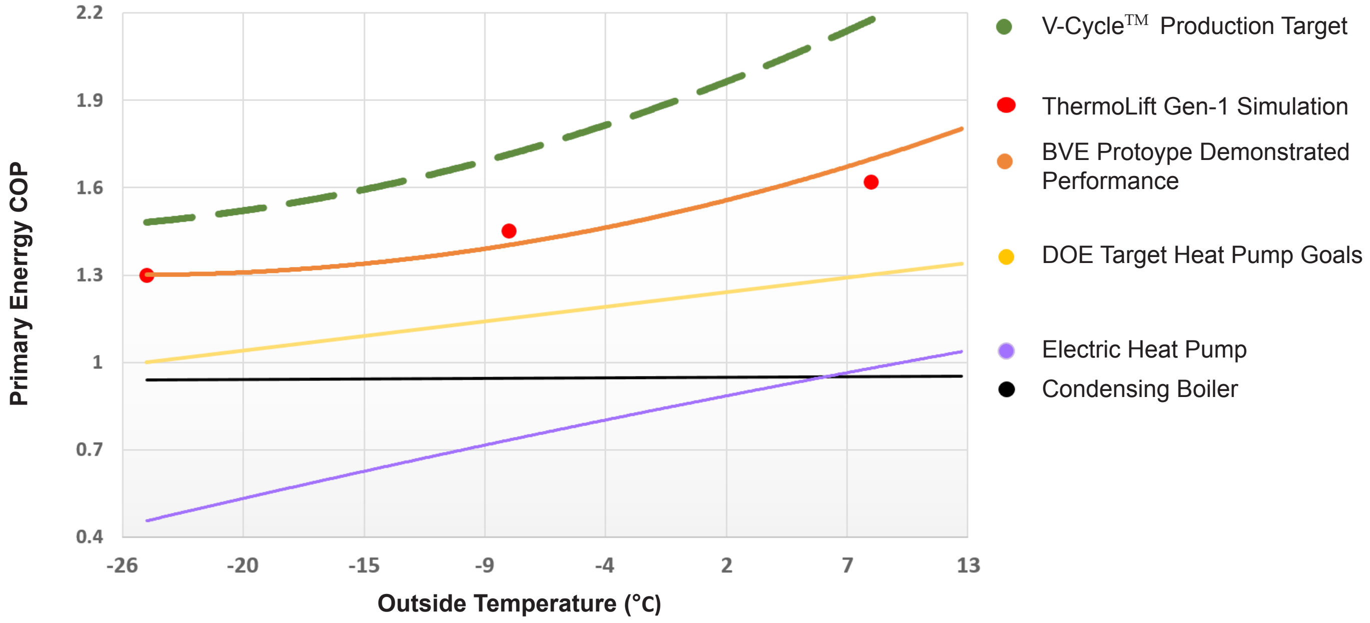

Figure 1. Comparison of Primary Energy COPs / Efficiencies for State-of-the-Art heating systems

For heating, state-of-the-art (SOA) furnace and boiler systems have reached their efficiency limits (Fig. 1); under high-heat load conditions, the efficiency often drops. Electric heat pumps have been available for many years, but with limited market shares in some geographic areas.

Further, the long payback period of high-efficiency systems has hindered their widespread adoption, resulting in an installed base dominated by low-efficiency/low-cost units. Meanwhile, the NO_x, CO_2 and small-particulate matter emitted into the atmosphere from space- and water-heating equipment reduces local air quality and can be toxic.

Current SOA A/C systems are still primarily electrically driven and operate during the hottest times of the year, when electricity is most expensive and the grid is at capacity, or exceeding it. This creates substantial stress, limiting grid efficiency and reliability and highlighting the growing importance of reducing our dependence on electrical systems. In addition, these energy-intensive vapor compression-based systems rely on harmful refrigerants known to be up to thousands of times more potent as greenhouse gases than CO_2. These greenhouse gases present an increasing variety of environmental concerns, including ozone depletion and climate change, and the full long-term consequences remain unknown.

Vuilleumier Cycle Thermodynamics

The Vuilleumier Heat Pump (VHP) can be thought of as a heat engine directly coupled to a heat pump (Fig. 2). Fuel is burned to produce a high-temperature heat source at temperature T_H, typically 700 °C (1 300 °F). This heat source provides heat Q_H to power the heat engine. Waste heat from the engine, Q_W, is discharged to the warm-temperature reservoir at temperature T_W, typically 60 °C (140 °F), which represents the heat source for the house. Work W from the heat engine is coupled directly to the heat pump, which pumps heat from the outdoor ambient at temperature T_C, typically -25 °C to 10 °C (-15 °F to 50 °F). The total heat delivered to the home is $Q_H(1+\eta\beta)$, where η is the heat engine efficiency and β is the heat pump coefficient of performance. For a traditional boiler or furnace, the maximum heat that can be delivered is the heat of combustion, Q_H assuming a 100 % efficiency.

The VHP can deliver an extra 40 % to 60 % of renewable heat energy extracted from the ambient air to supplement this combustion energy, leading to dramatically improved

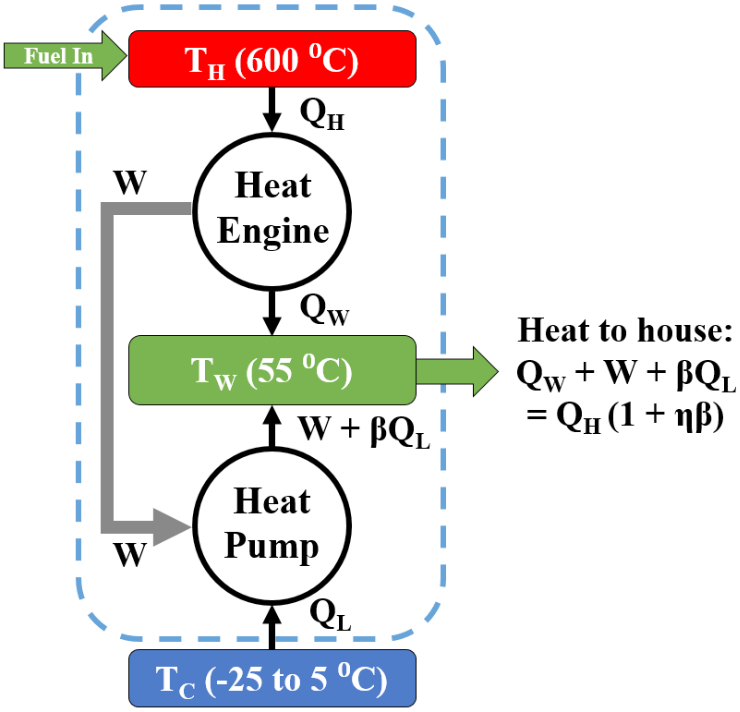

Figure 2. Diagram of integrated heat pump concept in heating mode demonstrating operational advantage

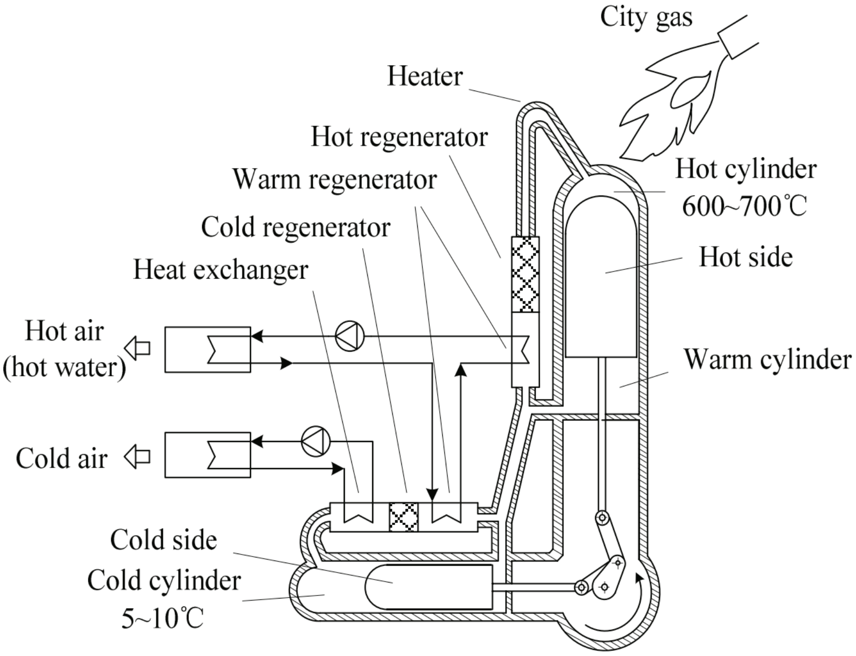

Figure 3. Configuration of traditional V-shaped thermally-driven Vuilleumier heap pump

efficiency and significant energy and emissions savings.

Thermodynamically, the direct integration of the heat engine and the heat pump or refrigerator is accomplished through a shared working fluid volume. The traditional Vuilleumier device features two mechanically linked displacers in V-shaped cylinder arrangement (Fig. 3). These reciprocating displacers continually redistribute the working fluid, helium, between three closed but connected chambers of constant temperatures. Each heat pump also contains at least three heat exchangers, which are responsible for capturing the heat derived from the external combustion source and exchanging heat with the building or the ambient, depending on the application.

Similar to a Stirling cycle device, porous metal components called regenerators act like thermal capacitors, periodically removing or depositing heat into the working fluid as it's shuttled throughout the machine. The device's V-shape roughly maintains a 90-phase angle difference between each displacer using a common crankshaft, resulting in a sinusoidal motion of the displacers. As the gas moves around the chambers, heat is extracted and captured in the thermally isolated chambers/heat exchangers and isochorically transferred to and from the regenerators, resulting in adiabatic thermal compression and expansion. Gas forces from the oscillating changes in temperature and pressure in the heat engine are directly transferred through the shared working fluid to drive the refrigeration cycle for the heat pump displacer. The magnitude of this characteristic pressure wave is a function of the system temperatures, average pressure, dead volume and regenerator performance.

Integrated external combustion heat pumps, such as the Vuilleumier heat pump, offer numerous benefits over other thermally driven cycles, including absorption and engine-driven vapor-compression systems. The combination of components, such as heat exchangers, limits the number of unique parts and therefore manufacturing costs. The internal displacers can utilize relatively low-frequency (< 10 Hz) short-stroke (< 5 cm) oscillations which require little to no energy to drive the system, besides the amount needed to overcome flow resistance and mechanical friction. The absence of a phase change in the Vuilleumier cycle eliminates common refrigerants which are toxic, corrosive and environmentally harmful, and enables the device to operate efficiently over a larger range of temperatures. The external combustion system is substantially simpler than traditional internal-combustion engines and is fuel-agnostic. Finally, the direct integration of the VHP leads to higher theoretical efficiencies.

This advantage can best be illustrated by considering a current SOA refrigerator or A/C where the heat pump, located at the building site, is completely decoupled from the heat engine at the power plant, requiring numerous energy conversions and generation and distribution losses.

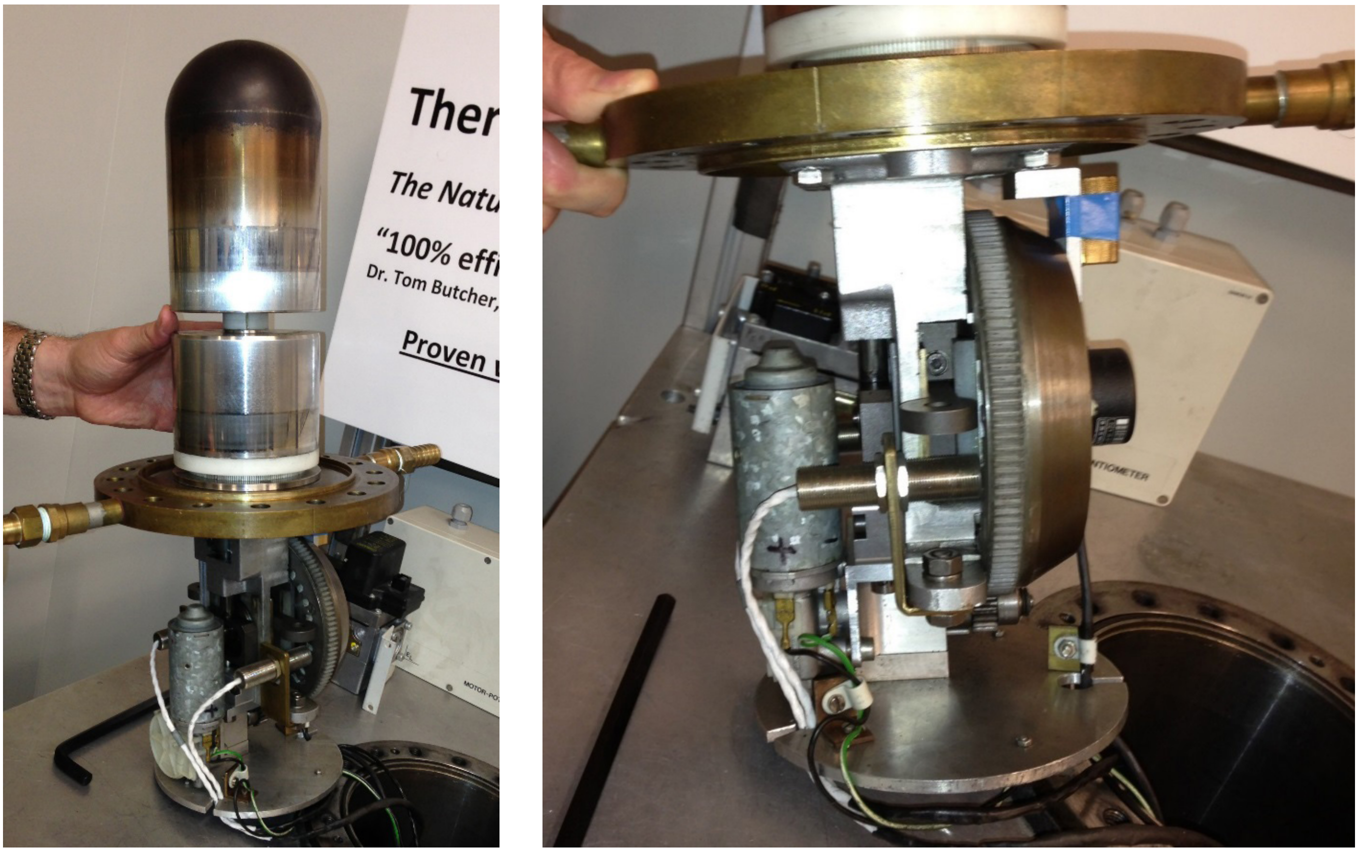

Figure 4. Pictures of BVE's mechanically-driven 4kW VHP prototype

Previous VHP Research

The potential advantages of the Vuilleumier cycle have motivated a handful of research groups to pursue development programs since the original invention and patent by Rudolph Vuilleumier in 1918. From the early 1960s to the late 1970s, researchers at the Technical University of Munich, Philips Research Laboratories, the U.S. Air Force and NASA, among others, built small VHPs for cryogenic applications. Some of these projects evolved into larger scale (10-20 kW) domestic HVAC projects and a new effort by Sanyo, in collaboration with various Japanese utilities, was started in the 1980s. While many of these prototype devices demonstrated efficient heating performances (COP > 1.3), none were completed to full commercialization.

The most comprehensive research program was completed by a collaboration between the Technical University of Dortmund and Bosch-Viessmann Energie (BVE) in the 1990s. Three prototypes of the original mechanically driven system were developed, each tested successfully for at least 6 500 hours and, cumulatively, for over 22 000 hours (Fig. 4). This research program was highly successful in producing qualitative and quantitative results based on direct measurements, all of which are well-documented and published in several manuscripts.

Results from this investigation demonstrated very high COPs from the mechanical system. The COP for heating was 1.65 at 8 °C, 1.45 at -8 °C, and 1.3 at -25 °C. These proven performance benchmark results created a very attractive foundation for future investigations to pursue the development of novel VHP compressor-less HVAC and HW solutions.

Modern Innovation

ThermoLift, a startup founded in 2012 and based at the Advanced Energy Research & Technology Center at Stony Brook University, is currently modernizing the Vuilleumier cycle for the small commercial and residential HVAC market. To date, the project has received nearly $5.8 million in funding, including private capital and grants from both the U.S. Department of Energy and the New York State Research and Development Authority for the development of a novel VHP.

The V-Cycle™ system is a natural gas-driven air conditioner and heat pump that can replace building heating, cooling, and hot-water systems with a single appliance. This appliance is an improved VHP that can provide a 30 % to 50 % reduction in energy consumption and costs related to building heating and cooling as well as associated reductions in greenhouse gas emissions.

Engineers are using the latest tools and innovations to optimize the proven Vuilleumier cycle, thereby minimizing manufacturing costs and consumer prices, improving thermodynamic efficiency, reducing annual operating costs, improving durability for extended lifetimes, and creating flexibility in the Vuilleumier cycle for improved seasonal performance and demand response capabilities.

ThermoLift's core innovation relates to a fundamental change in the motion of the displacers. Prior Vuilleumier devices relied on mechanically-synchronized fixed phase-angle displacers. In the past few decades, numerous industries, primarily in the transportation sector, have innovated in the field of electronically controlled actuators. Engineers are leveraging these technologies to create a free-piston VHP featuring independently controlled displacers.

This results in two distinct thermodynamic advantages. First, the independent discontinuous motion can eliminate purely sinusoidal motion, which enables better control over the location of the working fluid, increasing the theoretical magnitude of the characteristic pressure wave. Second, the incorporation of electronic controls creates the opportunity to change the cycle depending on the site-specific environment. Simple software changes to the electronic controls can adapt to different ambient conditions or different building parameters, and can utilize potential advantages of grid demand response to maintain the optimal efficiency in any load condition.

Using multiple robust 1D thermodynamic simulation programs, as well as 3D computational fluid dynamics and mechanical finite element analysis, engineers have designed and analyzed each component to optimize its thermal and mechanical performance. Additionally, decades of collective experience in engine design and mass manufacturing provide a critical knowledge base for creating high-performance, cost-effective components and techniques. ThermoLift has designed, simulated, built, and tested a first-generation prototype (Fig. 5). Using

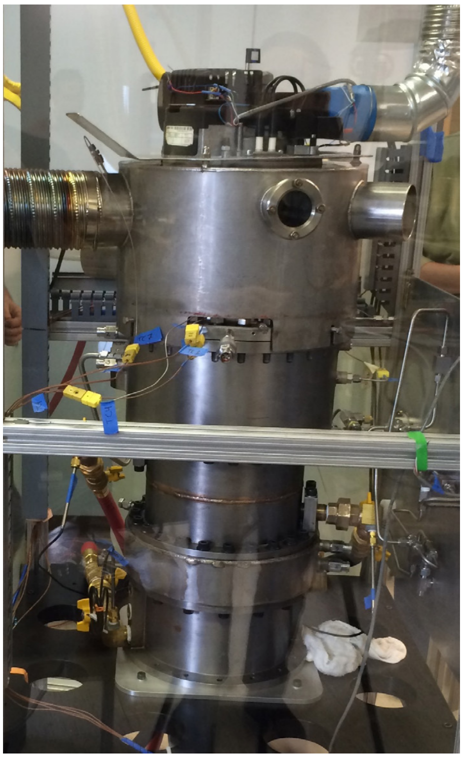

Figure 5. Picture during testing of ThermoLift's first generation prototype, featuring independent electronically controlled displacers

knowledge gained from these efforts, the company has now designed and started manufacturing a second-generation prototype. While the prior demonstrator validated the thermodynamic concepts in an updated mechatronic VHP, engineers have incorporated core innovations aimed at reducing manufacturing costs, increasing durability, and optimizing system efficiency before pilot demonstrations in 2016 and eventual large-scale commercialization.

Impact and Conclusions

Current projections for the efficiency of an enhanced Vuilleumier heat pump exceed the targets for next-generation heat pumps as outlined by the U.S. Department of Energy, achieving a heating COP > 1.2 at an ambient temperature of -25 °C. As a heating system, VHPs maintain high efficiency even in low-temperature environments; as a cooling system, VHPs can eliminate the need for compressors/refrigerants and help shift the energy load from the overburdened electric grid to natural gas, offering reliability advantages to utilities and cost advantages to consumers. The single appliance VHP will provide a 30 % to 50 % reduction in HVAC and HW energy consumption and costs, as well as associated reductions in greenhouse gas emissions. The technology is fuel-agnostic (e.g. natural gas, liquid fuels, solar, etc.) and is supplemented by heat energy from the surrounding environment.

Each year, millions of heating systems are sold in the cold climates of the United States, Canada, and across Europe. Fossil fuel and refrigerant regulations are constantly expanding and governments are putting more pressure on utilities to increase efficiency, especially in countries that rely heavily on imported energy. Modern VHPs are at the forefront of the shift from traditional HVAC solutions to high-efficiency low-cost systems that utilize the renewable heat energy in atmosphere. Continued development and innovation to the proven thermodynamics of the Vuilleumier cycle could help fill this critical need and result in tremendous economic and environmental impacts from wide-scale adoption in the marketplace.

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Overview of Deployment of Magnetic Refrigeration in Heat Pump Systems

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The majority of cooling systems are based upon vapor-compression refrigeration technology. Its principle has been unchanged for more than a century. Miniaturization and competitiveness have been gained, but there's still a need of alternative technologies, which can operate with better efficiency, lower energy consumption and better environmental safety. One of the most promising alternatives to a conventional vapor-compression system is magnetic refrigeration. In this article, an overview of the current state of development of a room-temperature magnetic heat pump is reported.

Introduction

The change in temperature of a magnetic material when applying or removing an external magnetic field under adiabatic condition is known to be the magnetocaloric effect (MCE). Magnetic refrigeration is based on MCE, which is an entropy change induced by magnetic field changes in a particular kind of material called a magnetocaloric material (MCM). The MCM generates and absorbs heat by the magnetic field changes as a magnetic refrigerant.

In 1918, Weiss and Piccard [1] discovered the MCE in a nickel sample. Its temperature rose by a few milli-Kelvin when moved into a magnetic field, and it cooled down again when it was removed out of the field. The first practical application of the MCE in the field of refrigeration at low temperature was proposed by Debye [2] and independently by Giauque [3] under the name of adiabatic magnetization/demagnetization. Then, since the 1930s, magnetic cooling has become a standard in cryogenics to cool down samples from a few Kelvin to a few hundredths of a Kelvin above the absolute zero point. It was in 1976 that the first device applying MCE at room temperature was developed [4]. In 1978, Steyert [5] introduced the principle of active magnetic regenerator (AMR). This was followed by another important development, namely the first magnetic refrigerator built by Astronautics Corporation [6]. These two studies have used gadolinium (Gd) as the MCM in their prototype.

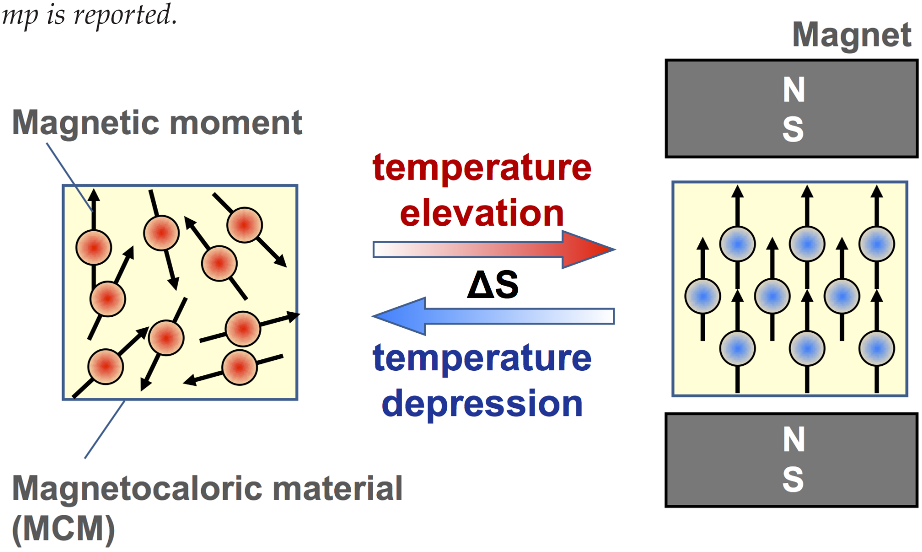


Figure 1. Illustration diagram of the principle of magnetocaloric effect

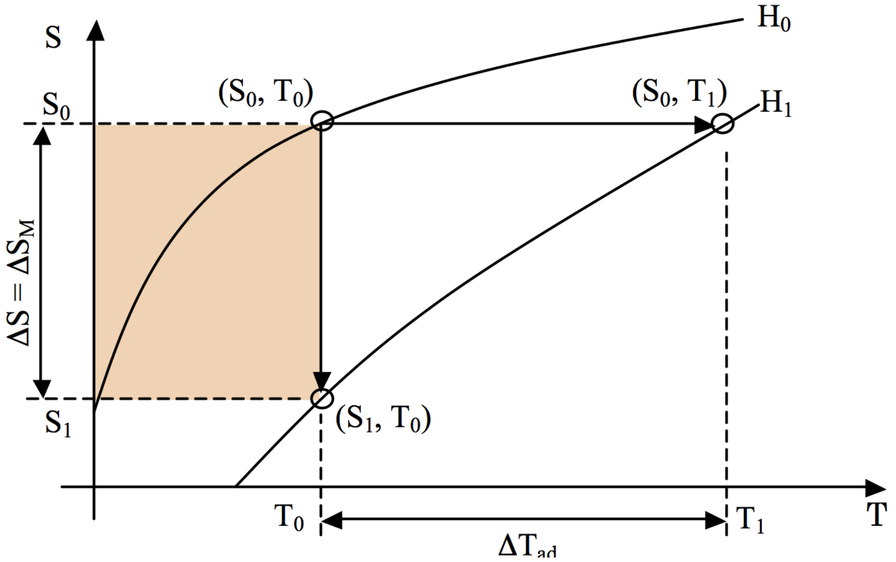


Figure 2. Temperature dependence of the total entropy S of a ferromagnet at constant pressure

Principle of MCE

The first scientific explanation of the MCE carried out by Weiss and Piccard [1] was based on the mean field theory. Nowadays it is common to explain the MCE through the concept of entropies (see figure 1). Figure 2 represents the temperature dependence of the total entropy S of a ferromagnet at constant pressure in the absence of magnetic field (H_0) and at a given magnetic field ($H_1>0$). The total entropy S is the sum of the magnetic entropy S_M, the lattice entropy S_L and the electronic entropy S_E as shown in Eq. (1).

$$S(T,H)=S_M(T,H)+S_L(T)+S_E(T)$$

Eq. (1)

For a given state of the material (S_0, T_0, H_0), a magnetic field H_1 could be applied following two kinds of processes. In the first one, if the temperature remains constant (isothermal process), the total entropy decreases until a point S_1 (T_0, H_1). When considering Eq.(1), the variation of the total entropy encountered in this case is equivalent to the variation of the magnetic entropy. This magnetic entropy change ΔS_M is equivalent to the formula in Eq. (2).

$$\Delta S(T_0,\Delta H)=\Delta S_M(T_0,\Delta H)=$$
$$S_0(T_0,H_0)-S_1(T_0,H_1)$$

Eq. (2)

In the second considered process, the magnetic field is applied adiabatically (i.e. S = constant). In this case the magnetic entropy decreases and in order to still have the total entropy remain constant, the temperature must increase. This variation of temperature is defined to be the adiabatic temperature change ΔT_{ad} as explained in Eq. (3).

$$\Delta T_{ad}(T_0,\Delta H)=T_1-T_0$$ ***Eq. (3)***

MCMs exhibit magnetic phase changes from a ferromagnetic to a paramagnetic state at their Curie temperature T_{Curie}. The Curie temperature is the temperature at which, in certain magnetic materials, a phase transition is induced from/to a ferromagnetic state to/from a paramagnetic state by a magnetic field change. The adiabatic temperature change ΔT_{ad} and the entropy change ΔS reach their maximum at T_{Curie}.

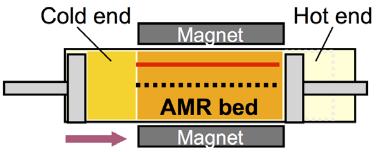
Essential information for a design and analysis of a magnetic refrigerator is the cooling capacity of the MCM. The maximum specific cooling energy of a MCM is directly related to the entropy and temperature change, which occurs due to a magnetization/demagnetization of the MCM.

Active Magnetic Regenerator

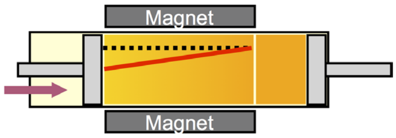
In a classic vapor-compression system, the refrigerant undergoes a phase change from liquid to gas and vice versa. The refrigerant moves and delivers energy from a low temperature source to a high temperature sink in the system via heat exchangers. In the magnetocaloric system, the refrigerant is solid and thus generates the necessity of using a heat transfer fluid to transport energy to different places of the system. Also, the MCM must be shaped in a porous structure in order to flow the heat transfer fluid through it. Most of the magnetocaloric materials show a large magneto-caloric effect in a rather narrow temperature interval. Therefore, they are not broadly applicable to any operation temperature. This is why layering with materials having different Curie temperatures is required.

The magnetocaloric properties of magnetic materials are not sufficient to directly use the MCE with a passive regenerator with reasonable magnetic field changes (circa 2 T when considering permanent magnets). In other words, the elevation in temperature of a MCM for a given magnetic field change under an adiabatic condition is not big enough to be directly employed in a "one shot" cycle, such as for example a strict Brayton or Ericsson cycle.

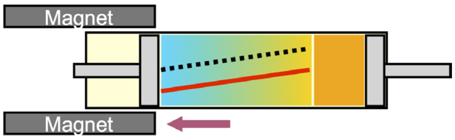
To overcome this problem, AMR are nowadays commonly used in magnetocaloric systems. An AMR is a crucial component of regenerative magnetocaloric systems and usually made of only MCMs. It is a compact heat exchanger that functions as an active thermal source and a thermal regenerator for the heat transfer fluid. Its global operation looks like a cascade refrigeration system of many cycles performed at each part of the regenerator. It allows an increase of both the temperature span and efficiency of the system (see figure 3).



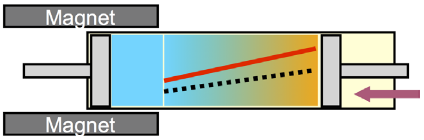
(1) Adiabatic magnetization



(2) Fluid flow: cold end to hot end



(3) Adiabatic demagnetization



(4) Fluid flow: hot end to cold end

Figure 3. Process of AMR

With the assumption of an infinite heat capacity of the regenerator compared to the one of the heat transfer fluid, the temperature profile inside the AMR during steady state regime does not change over the heat transfer fluid flow period and looks like the schematic drawing presented in figure 4.

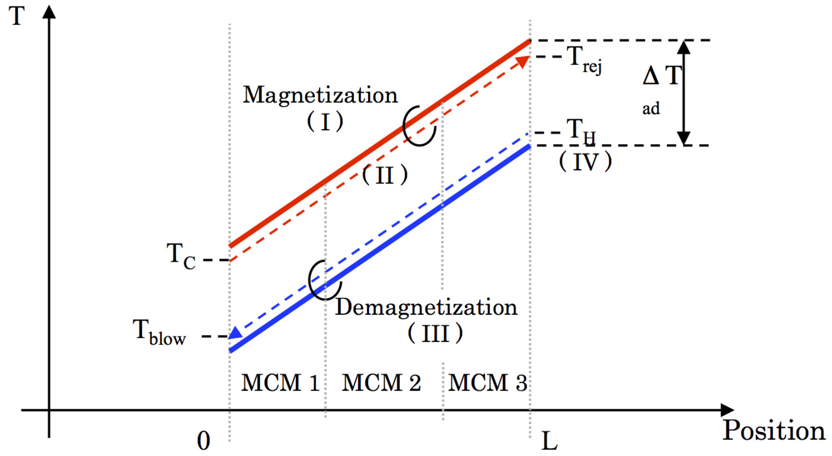


Figure 4. Temperature profiles inside AMR at cyclic steady state conditions

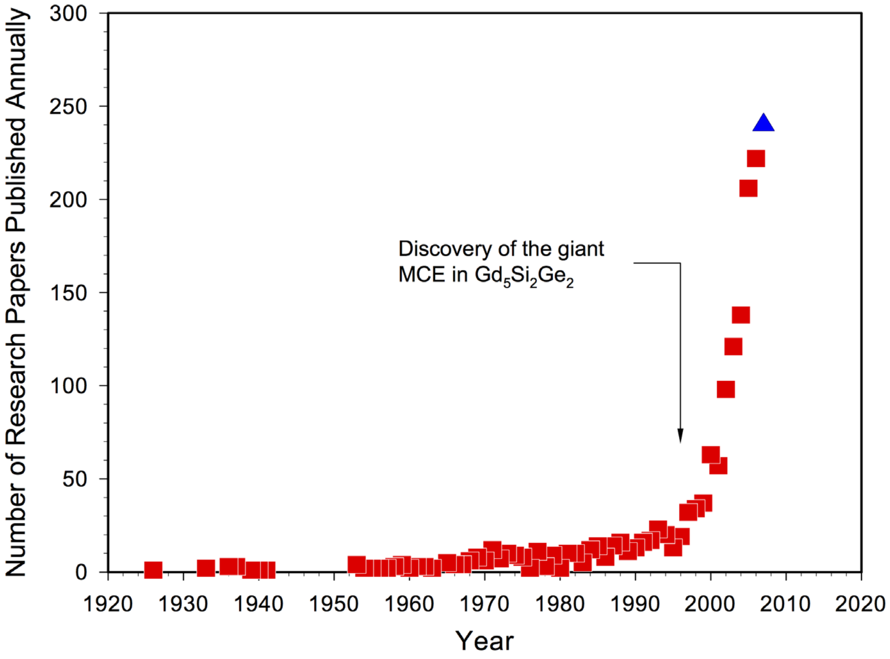


Figure 5. Annual number of papers published in magnetic refrigeration [8]

Solid lines represent the simplified solid refrigerant material temperatures and dashed lines represent the simplified temperature of the fluid during the flow process, when the assumption of an infinite heat capacity of the regenerator compared to the one of the heat transfer fluid is taken.

The operation of an AMR cycle is composed of four steps (see figures 3 and 4):

1. the magnetization of the AMR, which warms up due to the MCE;
2. the hot blow of the heat transfer medium moving from the cold source to the hot source;
3. the demagnetization of the AMR, during which the MCM matrix cools down due to the MCE;
4. the cold blow of the heat transfer medium through the AMR during the movement of the medium from the hot source to the cold source. The best running conditions would be close to Curie temperature in cyclic steady state conditions.

An AMR cycle consists theoretically, analogously as in the Brayton cycle, of two constant magnetic field (isofield) steps and two adiabatic steps. (At the difference that the AMR is porous and some fluid is trapped in the matrix). Each longitudinal point of the AMR undergoes a unique Brayton cycle and the whole regenerator undergoes a cascade Brayton cycle.

Milestone of Magnetic Refrigerator

A milestone of magnetic refrigerator technology was the discovery in 1997 of the giant magneto caloric effect [7]. Due to this publication and some following researches, magnetic refrigeration started to reveal a realistic potential for commercial room temperature applications at least for certain suitable market segments. Since then, an exponential number of publications (see figure 5) have been recorded, with a majority of these studies devoted to material sciences.

The scientific community is mainly composed of scientists and engineers coming from material, magnetism and thermodynamic. In 2005 the International Institute of Refrigeration, IIR/IIF – with its headquarters in Paris – reacted to these developments through the foundation of a Working Party on Magnetic Refrigeration. The institute attracted mechanical and thermodynamic engineers, refrigeration and fluid dynamic specialists, etc. to research in the “new” and alternative magnetic refrigeration domain. A series of international conferences, THERMAG I (2005), II (2007), III (2009), IV (2010), V (2012) and VI (2014) were held on different continents and led to a closer relation between the two scientific groups dealing with materials and machines.

Key points of the MCE technology

Advantages

Magnetocaloric materials (MCMs) used in magnetocaloric systems are solid refrigerants with zero ozone depletion potential (ODP) and zero global warming potential (GWP). We mean by solid that the refrigerant stays on earth without atmospheric release. This is not the case for most of the refrigerants, which are applied at present in conventional cooling processes. The best cooling efficiency of gas-compression refrigerators is known to reach 40 % of the Carnot limit, compared to 60 % for magnetic refrigerators working with Gd, despite the fact that Gd does not have the best MCE properties (as it can be appreciated in figure 6).

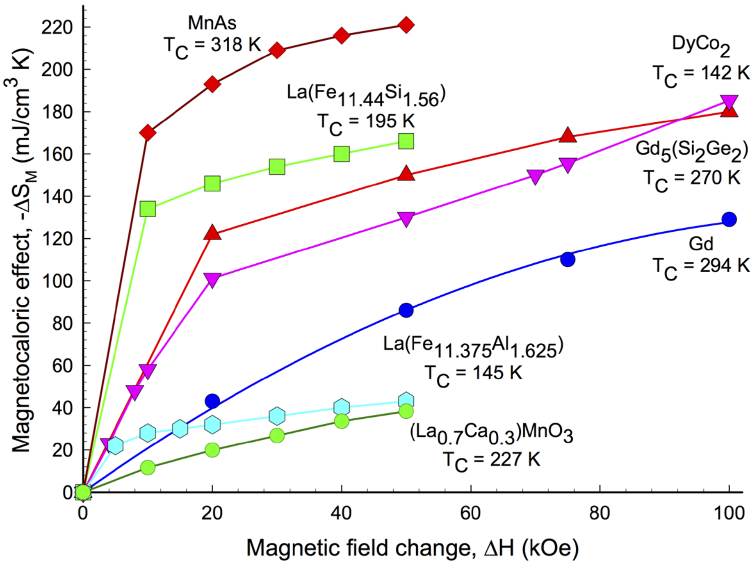
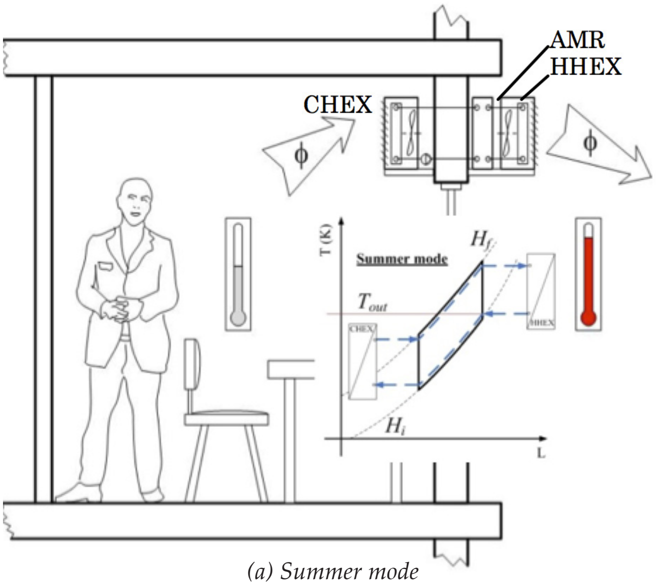


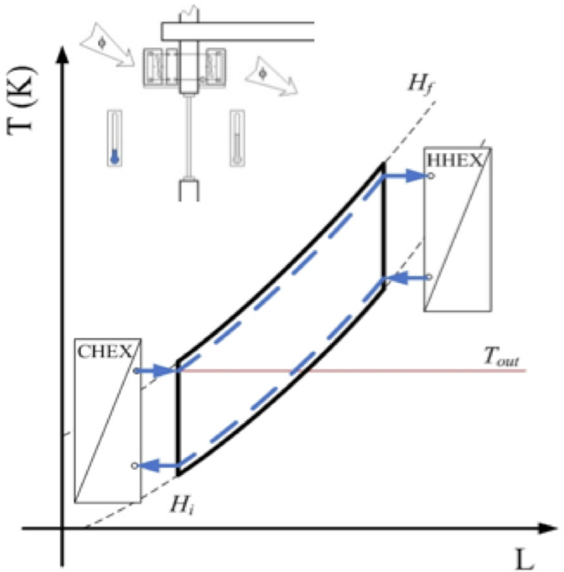
Figure 6. Representative MCMs belonging to the main family of alloy [8]

Potential

If magnetocaloric technology reaches the market, the biggest impact will probably hit the field of refrigeration, but applications in other sectors are also expected. It is well known that a refrigerator and a heat pump are based on the same principle. This is why, in analogy to magnetic refrigeration, magnetic heat pumping is also envisaged to be a real future concurrent to present technologies. For an illustration, an example of a polyvalent magnetocaloric machine for air conditioning is presented in figure 7. For the polyvalent magnetocaloric air conditioner the running conditions are described for summer mode in Fig. 7 (a), with the cold heat exchanger (CHEX) placed inside the room. In winter mode Fig. 7 (b), the CHEX is located in the outside environment.



(a) Summer mode



(b) Winter mode

Figure 7. Sketch of a polyvalent magnetocaloric air conditioner

Challenges and Perspectives for Practical System

The road to market holds issues, which must be overcome. In material science, most of the magnetocaloric materials show a large magnetocaloric effect in a rather narrow temperature interval, especially near Curie temperature. Therefore, if taken alone they are not broadly applicable to any operation temperature. However, layering with materials having different Curie temperatures results in temperatures for a practical system.

The development of better magnetic material with larger MCE (see Fig. 6) as well as better mechanical properties is expected. Compact magnets with higher attainable magnetic fields need to be developed, since the prototypes of magnetocaloric heat pumps are generally significantly larger in size and heavier than the corresponding vapor-compression systems.

For a practical system, the goal is to have an environmentally efficient and profitable machine. A better exploitation of MCE by using AMR, cascade operation, layered bed, higher frequency of operation and possibly some other technological breakthroughs would in any case help magnetic refrigeration to be more competitive.

It is clear that building a reliable, well performing and economical machine is still a big challenge and demands large efforts by avoiding the implementation of too expensive rare earth magnetocaloric compounds. This can be done by improving magnet design to decrease the weight of the magnet assemblies, by optimizing the devices in many aspects, and also by decreasing their energy use to improve the COP of the system. This especially applies to energy use caused by friction of the heat transfer fluid flow, which must be minimized.

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Thermal Response Testing for Ground Source Heat Pump Systems – Some History

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When designing ground heat exchangers used with ground source heat pump (GSHP) systems, a critical design property is the thermal conductivity of the ground. For larger ground heat exchanger installations, where knowledge of the ground thermal properties can help avoid undersizing or oversizing of ground heat exchangers, it is now common practice to measure the conductivity with a thermal response test (TRT). This article takes a historical perspective on the development of mobile TRT equipment and analysis procedures.

Introduction

An initial spurt of GSHP development in the 1940s and 1950s waned before a renewed interest in the late 1970s and early 1980s. New developments in the 1980s included development of design software which helped overcome some of the problems encountered in the 1950s. The availability of design software sparked an interest in helping system designers obtain needed inputs, including ground thermal conductivity.

A 1983 paper by Mogensen [1] suggested a method by which thermal conductivity of the ground and borehole resistance could be obtained in situ for a specific borehole using what we now call a thermal response test. Mogensen proposed use of the entire borehole as a probe, and the U-tube with fluid circulating through it as the “line source”. This was the starting point for work in the mid-1990s in both the USA and Sweden to develop mobile thermal response test devices.

This article is a condensed version of a much longer historical review article [2] covering early developments.

TRT Rig Development

Mogensen [1] proposed an experimental method to determine the thermal resistance between the heat carrier fluid and the borehole wall in a full-scale vertical ground loop. His proposed apparatus, which was to provide a constant cooling rate, was shown schematically with a water chiller, circulating pump and temperature recorder. Mogensen’s 1983 paper was the starting point for the authors of this paper when they began development of their mobile TRT rigs in the mid 1990s, even though they both concluded that it would be simpler to use a fixed heating rate to the borehole rather than a fixed heat extraction rate.

Figure 1. Mogensen’s (1983) cooling machine. Photo: Signhild Gehlin

Mogensen’s paper was entirely theoretical with no clear indication that a device had been fabricated or was even under development. However, we recently found that a 2.7 kW cooling machine (figure 1) was fabricated in 1982 and used on at least one TRT of a two-borehole ground heat exchanger in 1985. As this work was never published, it had no impact on later developments, which started with Mogensen’s 1983 paper.

Several full-scale response tests of installed systems with 25-100 boreholes were made by Swedish researchers between 1983 and 1992. The two researchers, Göran Hellström and Bo Nordell, discussed the possibility of developing a mobile TRT rig to support design of ground storage systems. This led to a student project at Luleå university, culminating in a test rig built in 1995 [3], see figure 2.

Figure 2. The OSU test rig on site in Lincoln, Nebraska in September 1998. Photo: Jeff Spitler

On the other side of the Atlantic, the design software GLHEPRO was developed as part of a research project and released in early 1994 and the developer’s attention turned to practical aspects of using the software. One of the most important questions was how users were to determine thermal properties of the ground for their site. Though the book Soil and Rock Classification for the Design of Ground-Coupled Heat Pump Systems-Field Manual [4] covered many rock types, the wide range of thermal conductivity for any one type of rock implied that identifying a specific rock type is insufficient for accurately determining its thermal conductivity (many rock types have conductivity ranges that vary by a factor of two to four).

In the spring of 1994, Dr. Jim Bose gave the first author (Spitler) a copy of Mogensen's paper. This led to some testing of the concept on an existing system and eventually to a project funded by the National Rural Electric Cooperative Association for development of a mobile unit for making in situ measurements.

In the meantime, the OSU team presented its plans and proposal to the Ewbank brothers, owners of a drilling and ground heat exchanger company (Ewbank and Associates, Enid, Oklahoma). The Ewbanks quickly built the first test rig, which was pictured in the February 1995 issue of the International Ground Source Heat Pump Association newsletter, The Source. Lessons learned with the Ewbanks test rig were very helpful in refining the plans for building the research-oriented OSU thermal response test trailer.

In May of 1995, funding for the research project on in situ measurement of ground thermal properties began, and a graduate student, Trey Austin , was hired to work on the project. The OSU team continued using the Ewbank test trailer through the fall of 1995, then fabricated their own trailer (figure 3) in the spring of 1996 [5]. By the end of 1996, the OSU team had performed 26 thermal response tests in Oklahoma, Texas, and South Dakota.

All three test rigs were of a similar design illustrated in figure 4, using electric resistance heaters and circulating pumps to impose an approximately constant heat flux on the borehole heat exchanger. Inlet and outlet temperatures, power input and flow rate were recorded. All three were mounted in trailers that could be towed by a car. The two Oklahoma trailers were large enough for the

Figure 3. The Swedish response test rig TED. Photo: Peter Gehlin

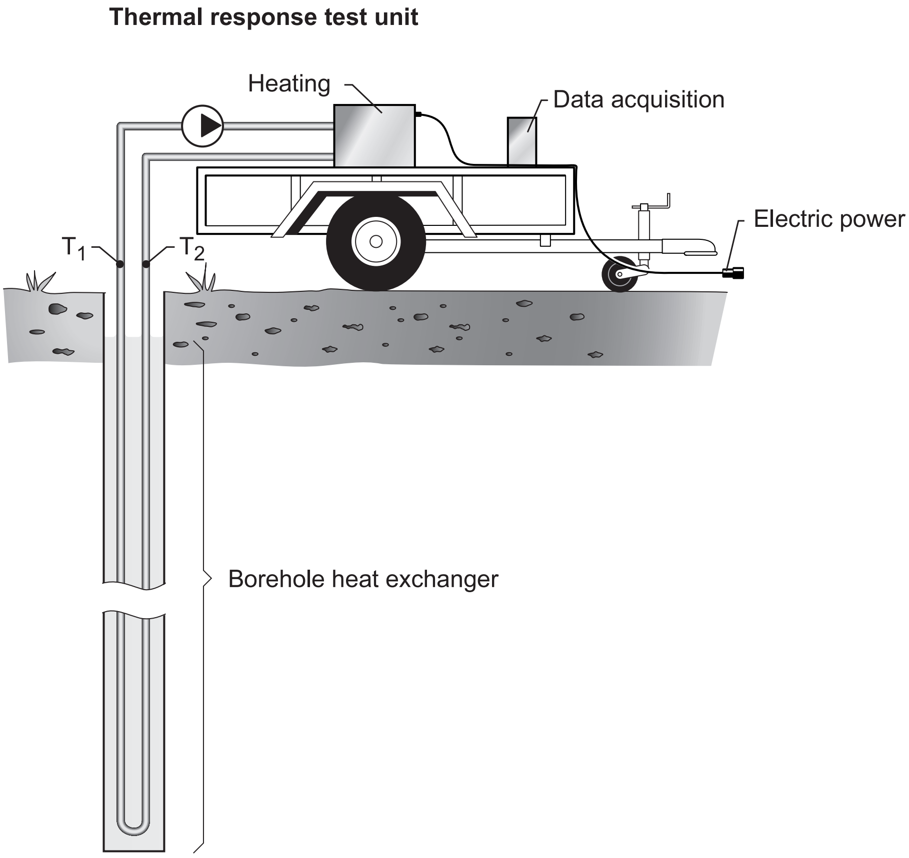

Figure 4. Typical TRT rig. Illustration: Claes-Göran Andersson

researchers to monitor the experiment from inside the trailer, while the Swedish trailer was smaller.

Both the US and Swedish test rigs were intended to impose a uniform heat pulse on the ground by means of using immersed electric resistance heating elements. However, the actual input to the ground can vary due to changes in the voltage supplied and heat losses or gains in the connecting piping. The OSU team attempted to reduce fluctuations in the supplied voltage by using a voltage regulator, but found the resulting improvements to be unsatisfactory. Variations due to heat losses or gains in the connecting piping were ameliorated by using thicker layers of insulation.

An alternative design was developed in 1997 [6] by the Dutch company Groenholland. A heat pump was used to provide heating and cooling, a buffer tank and 3-way control valve were utilized to provide very uniform heat injection or extraction rates.

This alternative design with active control of heat injection or extraction rates has the potential for eliminating influences of voltage fluctuations and environmental disturbances. It is, however, more complicated and expensive to construct. It also will necessarily have a higher uncertainty in the heat input rate – relying on measured temperature differences and flow rates will give higher uncertainties.

Selection of one design over the other will depend on the anticipated use of the TRT rig

Test Procedure Development

While Mogensen [1] suggested the general concept of the thermal response test, later researchers developed practical procedures for making the tests. These include heat input rate, flow rate, and test duration for single pulse tests.

Regarding heat inputs and flow rates, there are numerous practical considerations related to experimental accuracy. As a general rule, it seems advisable to keep heat transfer rates and flow rates similar to what is expected in practice.

The issue of test duration became an unexpectedly controversial subject. Austin, et al. [7] and Gehlin [8] recommended around 50 hours duration for sufficient accuracy, while some commercial providers of TRT in the USA felt strongly that sufficient accuracy could be achieved with shorter tests.

The OSU team experimented with multiple heat pulses with different heat injection rates, but found no discernible advantage over the single pulse, single heat rejection test when attempting to estimate ground thermal conductivity. For groundwater-filled boreholes, multiple pulse tests have been useful in showing how borehole thermal resistance can change with heat transfer rate and temperature

Analysis Procedures

As proposed by Mogensen [1] a simple analytical method known as the line source method was first utilized to determine the ground thermal conductivity from the temperature response. The line source method uses the solution to a pure conduction heat transfer process involving an infinite line source that begins generating heat continuously at time zero. This is often referred to as the Kelvin line source, crediting Lord Kelvin though it does not appear that he ever formulated this solution. Rather, later researchers derived the line source solution from Kelvin's work, and Mogensen cited the work of Ingersoll, et al. [9]. A key feature of the line source method is that, with one common approximation, the thermal conductivity of the ground can be determined directly from the slope of the temperature response when it is plotted against the logarithm of time.

As it turns out, when the heat transfer rate to the ground is maintained at a very constant level, the line source method gives accurate results. The OSU team noted the high degree of sensitivity of the line source method to variations in the heat transfer rate and therefore developed a parameter estimation approach which utilized a numerical simulation of a borehole coupled to an optimization routine. While a parameter estimation approach may estimate any number of parameters, the OSU team settled on estimating two parameters – ground conductivity and grout conductivity. In this case, the grout conductivity serves as a surrogate for all parameters that affect the borehole thermal resistance but which are difficult to know precisely: shank spacing and borehole diameter.

Validation

An important part of the early OSU research was validation of the measurements and estimation of the uncertainty. Two approaches [7] were taken to experimentally validate the measurements.

1. A 79 m deep borehole was drilled with a coring bit in Stillwater, Oklahoma. Thermal conductivities of the core samples were measured using a guarded hot plate apparatus and a layer-thickness-weighted average was computed.
2. A medium-scale laboratory experiment, sometimes referred to as the "sand box" was conducted, where the thermal conductivity of the medium (dry sand or saturated sand) was independently measured.

For both approaches, the parameter estimation procedure was able to match the independent measurements within ± 2 %.

Austin, et al. [7] also presented a detailed uncertainty analysis of the experiment and parameter estimation analysis and gave an estimated uncertainty for typical field conditions of ± 10 %. The comparatively accurate validation results were attributed to more accurate determination of input parameters than can typically be done for field measurements.

Conclusions

Mogensen [1] proposed using the line source model in conjunction with a borehole containing a U-tube and a test apparatus that could impose a constant heat flux to determine effective borehole thermal resistance, and, incidentally effective thermal conductivity of the ground.

Two projects, both with the aim of developing mobile experimental apparatus, test methodology, and analysis procedures were undertaken independently and roughly simultaneously in Sweden and the USA.

The projects resulted in several TRT devices installed in trailers allowing the equipment to be towed from site to site. The first tests with mobile TRT rigs were made prior to February of 1995 in the USA and in April of 1996 in Sweden. Though there was a short published account of an American TRT rig published in February of 1995, the first substantive account of TRT rig development and analysis procedures was in the 1996 Eklöf and Gehlin [3] master's thesis. More complete US publications [5, 7] with experimental validation of the test apparatus and procedures took several years more to publish.

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An Inside Story Behind the Advent of “Eco Cute” CO_2 Heat Pump Water Heater for Residential Use

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More than ten years have passed since the “Eco Cute” CO_2 heat pump water heater for residential use was commercialized in May 2001 in Japan through collaborative R&D including Central Research Institute of Electric Power Industry (CRIEPI). Cumulative shipments amounted to more than 4.6 million at the end of March 2015. There were two projects involving hot water supply heat pumps prior to the development of Eco Cute in CRIEPI, though neither went into commercial production. In this paper, the history and technical aspects of the advent of Eco Cute, including the former two projects, are introduced.

Introduction

More than ten years have passed since the “Eco Cute” CO_2 heat pump water heater for residential use was commercialized in May 2001 in Japan through the collaborative R&D of Tokyo Electric Power Company (TEPCO), Denso Corporation (DENSO) and Central Research Institute of Electric Power Industry (CRIEPI). It became widespread through the introduction of a subsidy by the Japanese government, market entry of new products and growing interest in environmental problems. Cumulative shipments amounted to more than 4.6 million at the end of March 2015 as shown in figure 1 [1].

There were two projects involving hot water supply heat pumps prior to the development of Eco Cute in our institute, CRIEPI, though neither went into commercial production. On this occasion, the history and technical aspects of the advent of Eco Cute, including the former two projects, are introduced.

History of Research & Development of Heat Pumps in CRIEPI

The R&D activities of heat pumps in CRIEPI began when it was entrusted with a part of the Super Heat Pump development project, which was a national project and started in 1984. Because heat pumps work on the same principle as thermal power generation cycle, a staff member of the thermal power section, who was senior to me, was assigned to play a central role in this research project. The CRIEPI decided to hire a new employee for the project, which led to me joining in 1986.

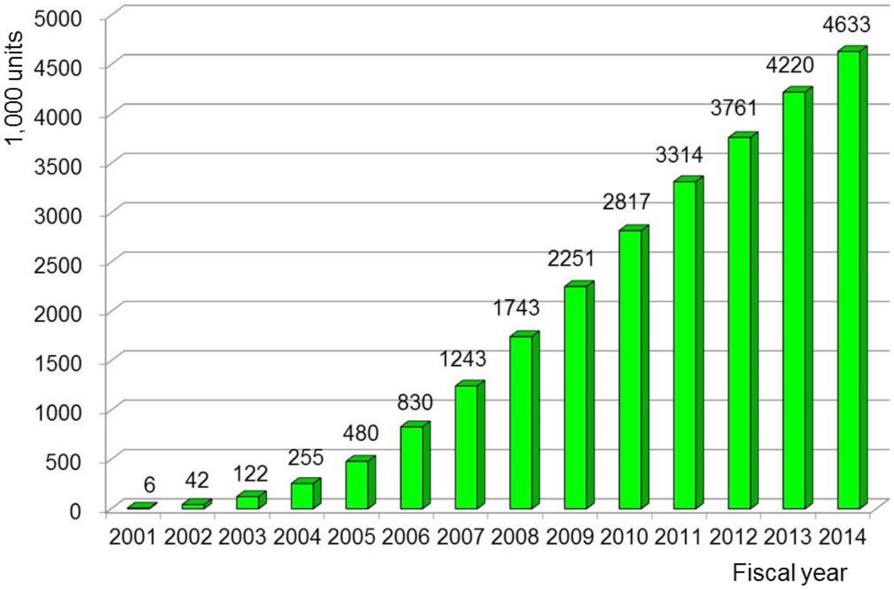
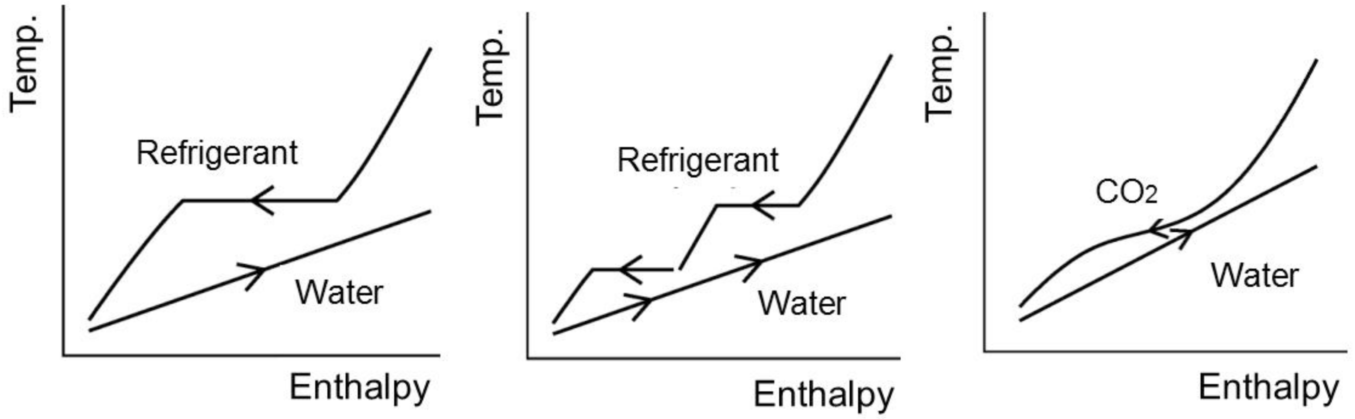


Figure 1. Cumulative shipments of “Eco Cute” CO_2 heat pump water heater for residential use in Japan. (Made from the statistical data, such as data provided by JRAIA [1])

Not only was the entrusted research conducted, but also the original research in CRIEPI was started, the sector in which the introduction of a heat pump could bring about a large energy saving effect was investigated. As results, it was found that major energy savings were possible if a highly efficient heat pump could be developed and introduced for domestic tap water heating. The demand for hot tap water accounts for about 30 % of residential final energy consumption, but most of this demand is met by the direct combustion of fossil fuel.

Under such a circumstances, a new system named the “two-stage compression and cascade heating heat pump water heater (TS-HPWH)” was invented by my senior staffer based on his knowledge and experiences in the field of the thermal power generation cycle. This system was later registered as a Japanese patent.

For a normal refrigerant such as Fluorocarbon, water or air is heated by a refrigerant that condenses at a constant temperature on the high



(a) Simple compression cycle

(b) Two-stage compression cascade heating cycle

(c) CO2 simple compression cycle

Figure 2. Comparison of heating cycle (Temperature - Enthalpy Diagram). Tap water is heated from 10 °C to 65 °C.

Figure 3. Experimental apparatus of two-stage compression system. Heating capacity 4 kW, installed in 1987.

pressure side of the heating cycle. For this reason, good efficiency can be gained if the heating temperature range is small, as seen in the cycle for air conditioning. On the other hand, for hot water supply, water of 10 °C needs to be heated up to 65 °C, thus requiring a heating process with a high temperature rise. Figure 2 (a) shows the heating process wherein water at 65 °C is made by a simple heat pump cycle. As shown in the figure, there is a section in which low temperature water at about 20 °C is heated by condensing refrigerant at about 70 °C, which results in large loss. A heating temperature of about 30 °C suffices to heat the water at 20 °C.

The TS-HPWH we had invented was intended to decrease the irreversible loss by preparing two condensation pressures through its two-stage compression. By doing so, it could achieve proper heating suitable for the temperature level shown in figure 2 (b). Next it was examined whether this system could actually be put into practical use and what kind of elemental technology would need to be adopted for it. In this respect, an experimental system apparatus was manually fabricated as shown in figure 3. Using this apparatus, the feasibility of its cycle was verified and good results were obtained.

Collaborative R&D with electric power companies and a manufacturer were conducted from 1988 to 1992 in order to develop the air conditioning & hot water supply heat pump for residential use based on TS-HPWH. The development progressed smoothly, evolving onto actual field tests. Despite these efforts, this apparatus was not made into a commercial product. The reasons for this were lower hot water supply efficiency than expected and

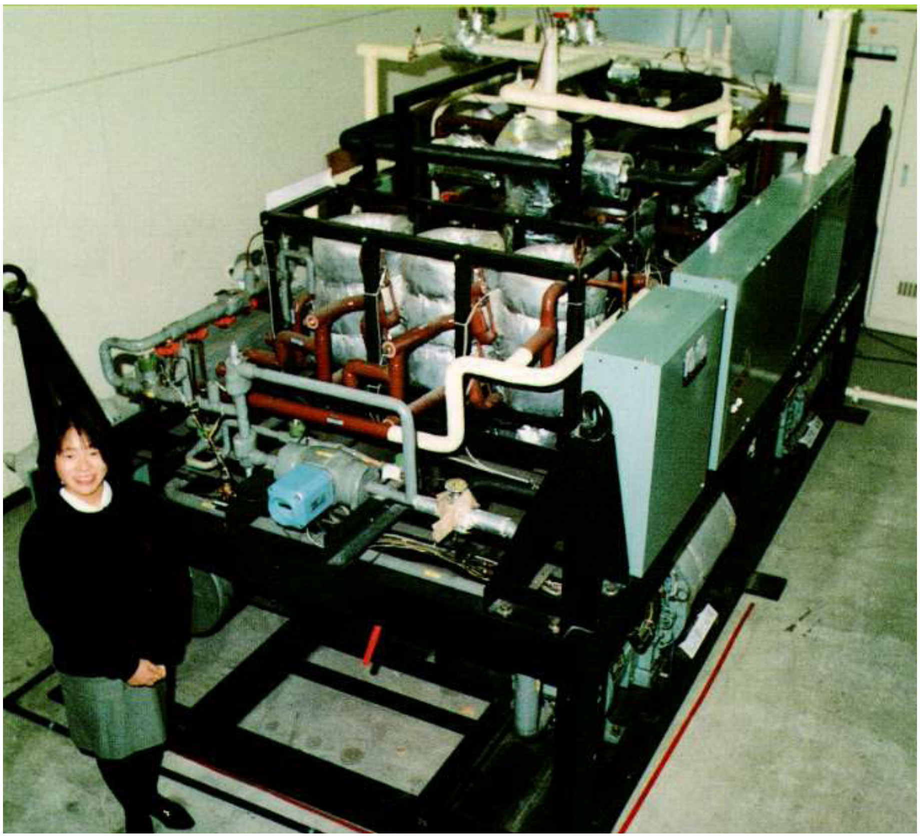


Figure 4. Prototype of two-stage compression system for business use. Heating capacity 150 kW, installed in 1991.

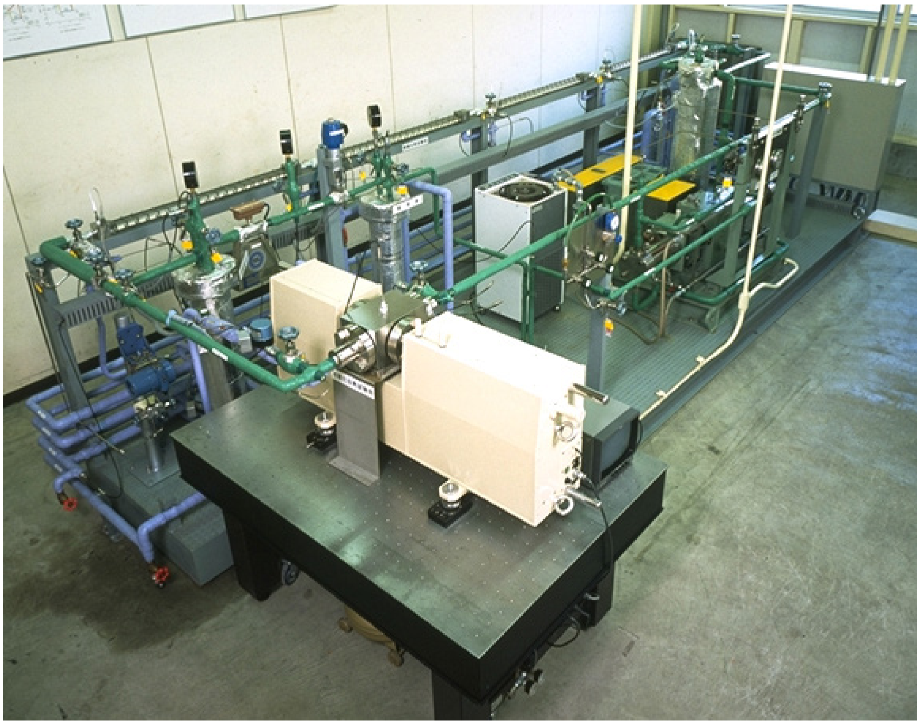


Figure 5. Basic experiment loop for CO_2 heat pump. Heating capacity 4 kW, installed in 1996.

its unattractiveness in terms of price, size and so forth. Instead, rather than a multifunctional heat pump, a heat pump equipped with only a hot water supply function was to be developed.

Having learnt from experience, the development of TS-HPWH for commercial use in hotels and other facilities was conducted from 1990 to 1996. A prototype was made as shown in figure 4. In order to produce this on a commercial basis, collaborative development with a manufacturer and a general contractor was initiated. The collaboration resulted in a basic system for commercial use and the development of its elemental technology. Unfortunately, a commercial system did not materialize because of issues surrounding Fluorocarbon. The developed system was very good from a technical standpoint, particularly because it was designed specifically for hot water supply. Nevertheless, the development was run at an inopportune time.

Thus, two collaborative developments were conducted, but neither resulted in commercial products. Two younger colleagues joined us, so four employees now worked on the R&D project at CRIEPI, with some funds invested in the ongoing project. Accordingly, R&D of heat pumps was under increasing pressure in-house, with questions being asked as to the progress of our heat pump research.

Investigation of natural refrigerants and encounter with CO_2 refrigerant

One of the main reasons for the failure of the commercialization of the two-stage compression system for commercial use was an issue surrounding the use of fluorocarbon refrigerants. At that time, CFC-12 was used for two-stage compression systems, and generally, refrigerants in the HFC family had become promising alternatives to conventional refrigerants in Japan and the

United States. In Europe, the move was toward examining natural refrigerants. Considering these facts, in 1993 our investigation turned towards the idea of examining natural refrigerants from a long-term viewpoint.

Among natural refrigerants, CO_2 was focused on because it has unique properties. Basic studies began in 1995. It was confirmed that a higher COP can be theoretically obtained from CO_2 than any other refrigerant when making hot water. The reason is described in figure 2. It can be seen from figure 2 (c) that CO_2 does not condense, unlike normal refrigerants, and that its temperature decreases gradually as water is heated. For this reason, irreversible loss is reduced, bringing about a higher COP than for fluorocarbon refrigerants. Though the two-stage compression system had been invented previously, the use of CO_2 enabled us to produce almost ideal hot water heating. Back in those days, R&D of CO_2 refrigerants was already underway in Europe, but not in Japan. So a basic experiment loop for a CO_2 heat pump was designed, fabricated and installed (figure 5) in March 1996. At that time, there was no compressor available capable of operating on CO_2 pressure. For this reason, a company that was small in size but specialized in high pressure gas processes was found and it made the compressor for the loop. Using the experiment loop, the feasibility of the CO_2 cycle, its control method and heat transfer were investigated. As a result, it confirmed that CO_2 was a promising refrigerant for hot water supply.

Joint development of CO_2 heat pump water heater

In March 1998, when it had been found that the CO_2 refrigerant could be put into practical use and was a promising refrigerant for hot water supply, a sales representative from TEPCO visited CRIEPI to inquire into natural refrigerant technologies for use in air conditioning.

Figure 6. Test chamber for prototype of CO_2 heat pump water heater. Heating/cooling capacity 5 kW, installed in 1999

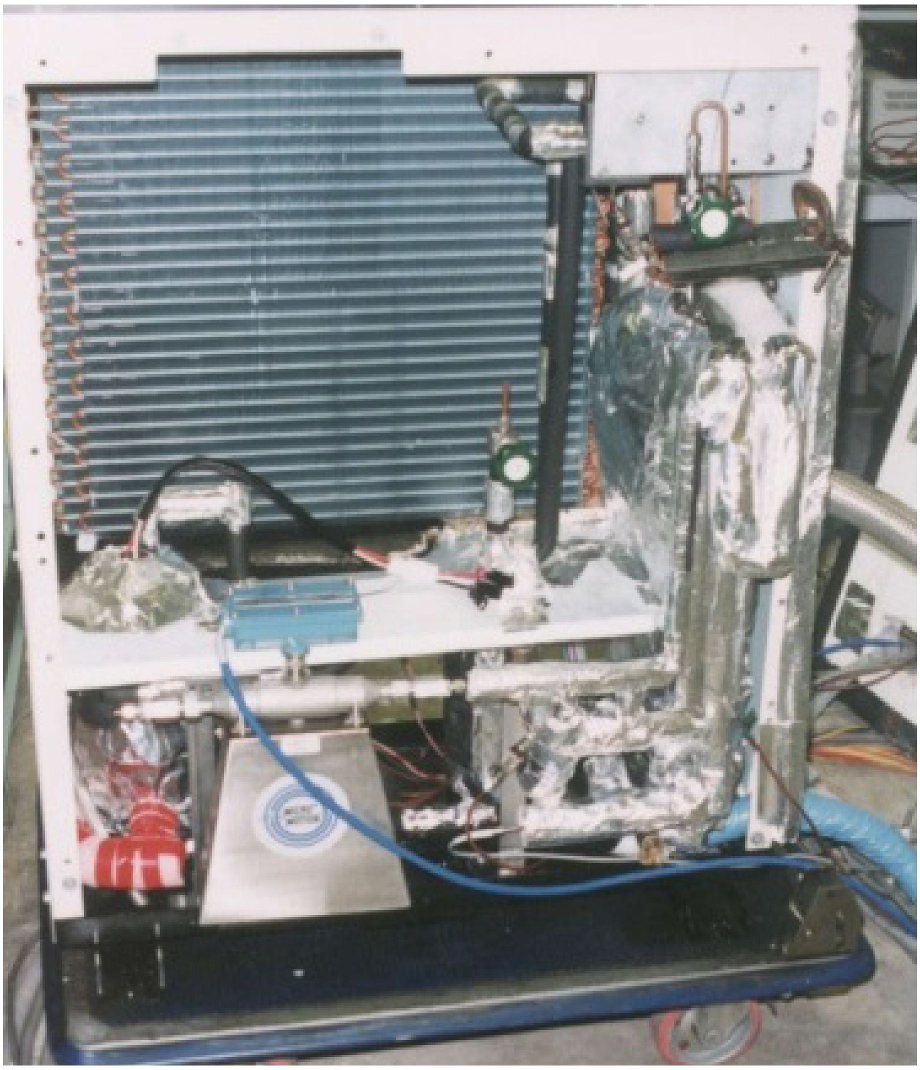


Figure 7. Prototype of CO_2 heat pump water heater for residential use. Heating capacity 4 kW, installed in 1999.

Figure 8. Eco Cute at my home. Heating capacity 6 kW, tank capacity 460 l, 2004 model.

Explaining that CO_2 was a good refrigerant for hot water supply, he understood the excellent properties of CO_2 as a refrigerant for a heat pump water heater. Consequently, in-house arrangements for the development of both companies were started. However, it is true that only a manufacturer can actually produce a product, so it was necessary to find a manufacturer to be able to participate in our development.

In May of the same year, 1998, an international conference on natural refrigerants was held in Europe. CRIEPI participated in the conference and made a presentation about the results of basic studies of a CO_2 heat pump. DENSO from Japan also presented the development of a CO_2 car air conditioner. While listening to the presentation, it became clear that DENSO could develop a CO_2 heat pump water heater. Numerous meetings were held at the conference, between CRIEPI and DENSO. In July, a representative from TEPCO visited DENSO and discussed a joint development project. Initial reactions were not completely positive as DENSO was a car air conditioner maker. However, once the development technology was explained, DENSO agreed to the offer. In effect, the joint development project began in October.

During the joint development, a wind tunnel for testing a prototype of the CO_2 heat pump water heater was installed in CRIEPI as shown in figure 6 (1999). A lot of tests on the prototype (figure 7) were performed using the wind tunnel. Measuring, analyzing and evaluating COP and efficiencies of elements were conducted. Development issues were abstracted and measures for performance improvements were investigated. Improved components were sent to CRIEPI by DENSO. These components were assembled, tested and evaluated, and then results were returned to DENSO. This cycle was repeated over and over again. Finally, it was confirmed that our initial goal of the developed technology could be attained.

Anyway, after many ups and downs, the “Eco Cute” was commercialized for the first time in the world in May 2001. The saying, "third time lucky" surely applies to CRIEPI. Past experiences from the two previous failed attempts at commercialization contributed greatly to the success of this development project.

Conclusion

This paper has looked at the difficulties encountered prior to the advent of Eco Cute being introduced. Looking back on the development of Eco Cute, it really got started in a timely fashion with good connections between people, each of whom had their own role to play. In the end a good outcome was achieved through each of us working towards the same goal. The Eco Cute that was installed in my home is shown in figure 8. Taking responsibility as a developer, it was purchased in 2004 and has been used for more than 10 years. In the heavy snow of February 2014, it failed, yet after repair, it once again started to produce hot water.

Acknowledgement

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[1] *http://www.jraia.or.jp/english/excel/shipments_fy_e.xls*

Events

2015

2 – 4 December
46th International HVAC&R Congress and Exhibition
Belgrade, Serbia
http://kongres.kgh-kongres.rs/index.php?lang=en

3 – 4 December
13. Forum Wärmepumpe (The conference language is German)
Berlin, Germany
http://www.bwp-service.de/

2016

23 – 27 January
ASHRAE Winter Conference
Orlando, USA
https://www.ashrae.org/membership--conferences/conferences/2016-ashrae-winter-conference

9 – 10 February
ATMOsphere Asia 2016
Tokyo, Japan
http://www.atmo.org/asia2016

23 – 26 February
HVAC&R JAPAN 2016
Tokyo, Japan
http://www.hvacr.jp/en/index.html

31 March– 2 April
12th International HVAC+R & Sanitary Technology Symposium
Istanbul, Turkey
http://www.ttmd.org.tr/sempozyum2016/eng/

7 – 9 April
4th IIR Conference on Sustainability and the Cold Chain
Auckland, New Zealand
http://www.iifiir.org/medias/medias.aspx?INSTANCE=exploitation&PORTAL_ID=general_portal.xml&SETLANGUAGE=EN

15 – 17 May
8th Asian Conference on Refrigeration and Air Conditioning
Taipei, Taiwan
http://www.acra2016.org/index.php?po=welcome

18 – 20 May
11th IIR Conference on Phase Change Materials and Slurries for Refrigeration and Air Conditioning
Karlsruhe, Germany
http://www.hs-karlsruhe.de/pcm2016.html

22 – 25 May
12th REHVA World Congress - CLIMA2016
Aalborg, Denmark
http://www.clima2016.org

25 – 29 June
ASHRAE Annual Conference
St. Louis, USA
http://ashraem.confex.com/ashraem/s16/cfp.cgi

3 – 8 July
The 14th International Conference of Indoor Air Quality and Climate
Ghent, Belgium
http://www.indoorair2016.org/

11 – 14 July
Purdue Compressor, Refrigeration and High Performance Buildings Conferences
West Lafayette, USA
https://engineering.purdue.edu/Herrick/HomepageFeatures/2016-purdue-conferences-july-1114

10 – 12 August
ASHRAE and IBPSA-USA SimBuild 2016: Building Performance Modeling Conference
Salt Lake City, USA
http://ashraem.confex.com/ashraem/ibpsa16/cfp.cgi

21 – 24 August
Gustav Lorentzen Natural Working Fluids Conference
Edinburgh, Scotland
http://www.ior.org.uk/GL2016

11 – 14 September
7th International Conference on Magnetic Refrigeration at Room Temperature
Torino, Italy
http://www.thermag2016.com/

19 – 24 September
European Geothermal Congress 2016
Strasbourg, France
http://europeangeothermalcongress.eu/

22 – 23 September
2nd International Conference Efficient Building Design: Materials and HVAC Equipment Technologies
Beirut, Lebanon
https://www.ashrae.org/membership--conferences/conferences/2016-2nd-international-conference-efficient-building-design

23 – 26 September
9th International Conference on Indoor Air Quality Ventilation & Energy Conservation In Buildings
Seoul, Republic of Korea
http://iaqvec2016.org/

11 – 13 October
Chillventa
Nuremberg, Germany
http://www.chillventa.de/en/

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Volume 34 - No. 1/2016

Front page references

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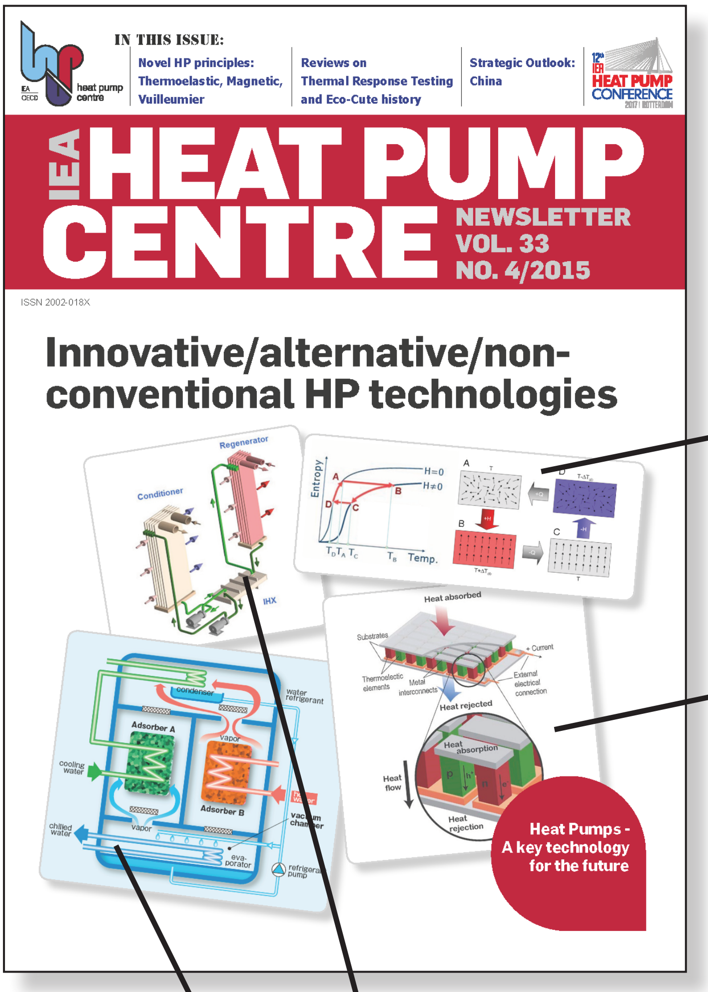

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Reviews on Thermal Response Testing and Eco-Cute history

Strategic Outlook: China

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ISSN 2002-018X

Innovative/alternative/non-conventional HP technologies

Heat Pumps - A key technology for the future

Magnetocaloric principle; magnetic cooling cycle
Image source: William Goetzler, Navigant, MA, USA - http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_refrig_report_10-09.pdf

Thermoelectric principle; thermoelectric devices
Image source: Jeffrey Snyder, Northwestern University, IL, USA - http://thermoelectrics.matsci.northwestern.edu/thermoelectrics/engineering.html

Standalone Liquid Desiccant Air Conditioner
Image source: Andrew Lowenstein, AIL Research, Inc., MA, USA - http://ailr.com/liquid-desiccant/ld-tutorial/

Adsorption principle; adsorption chiller
Image source: Eric Delforge, Mayekawa Europe - http://www.mayekawa.com.au/wordpress/wp-content/uploads/2013/07/AdRef-Noa-Brochure-170713.pdf

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster co-operation among its participating countries, to increase energy security through energy conservation, development of alternative energy sources, new energy technology and research and development.

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International collaboration for energy efficient heating, refrigeration and air-conditioning

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The IEA HPT strives to achieve widespread deployment of appropriate high quality heat pumping technologies to obtain energy conservation and environmental benefits from these technologies. It serves policy makers, national and international energy and environmental agencies, utilities, manufacturers, designers and researchers.

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