Sustainable innovation – a technology review

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Introduction

Although refrigeration is an integral part of almost every person's life it is essential that refrigeration technologies continue to evolve and develop. In the UK alone, RAC (Refrigeration and Air Conditioning) equipment currently consumes around 16% of all electricity and is 50% of an average supermarket's energy demand. Sustainable solutions must therefore be at the centre of innovation and technology development for the future.

On a world scale the interrelated issues of global warming and security of provision of energy supply are going to become more acute in the future at a time when demand for RAC capacity in all sectors will be growing and temperature control requirements becoming increasingly challenging. Figure 1 shows the potential change in temperature in the UK by 2080. This will have a significant impact on our building, industrial processes and cooling applications and we can expect it to be increasingly challenging to provide sufficient cooling effectively and economically.

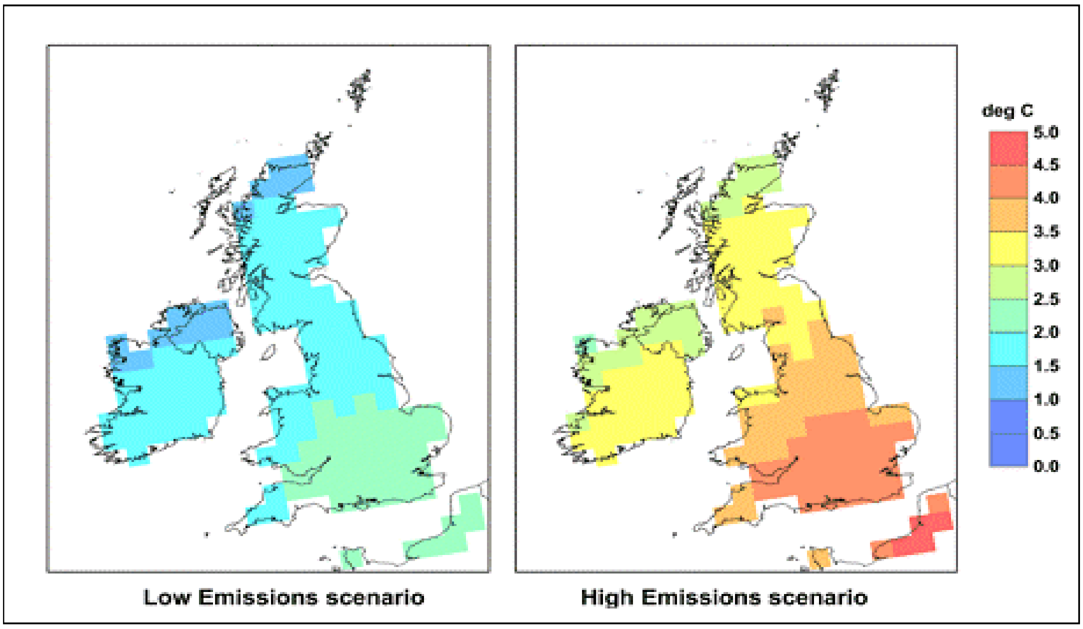

Figure 1. Predicted temperature change in the UK in 2080 [CIBSE, 2005]

In addition, in recent years we have seen an increase in the demands of both national legislation and internationally binding agreements which are having an influencing how we design, operate and maintain cooling technology. Much of this legislation is aimed at reducing environmental impact and whilst this may represent additional capital cost, it will also have the effect of supporting improvements in environmental performance of existing technologies, and encouraging the take up of new more sustainable technology.

Incremental changes are possible to existing technology for example, advanced materials and components can enable significant improvements in heat transfer resulting in COP improvements. This includes micro-channels which offer the opportunity to increase heat transfer coefficients to 10 times that of large bore tubes; vacuum insulation with its possibilities to provide large scale improvement in properties, as well as compressors magnetic bearings that enable high efficiency at full and part loads.

However, there are also renewable energy and novel cycles that are gaining increased profile and that are subject to even more rapid developments based on research and innovative application. The integration of renewable energy technologies with RAC can offer valuable synergies - for instance cold storage can provide an energy store or battery for intermittent wind power and solar powered air conditioning can provide cooling when the sun shines. Novel cycles still at the development stage, such as magnetic and electro-caloric refrigeration, could offer the potential to improve system efficiency still further. No doubt there are many additional technologies that the RAC sector could make use of which are still at research or concept state and that will help us to achieve even greater savings in the future.

Some may argue that the current world economic crisis is not the right time to be considering investing in sustainability or carbon efficiency. However, the development of low carbon technologies have been cited by both the US and UK governments as providing one of the mechanisms for escaping a recession. SIRAC, the network for sustainable innovation in refrigeration and air conditioning, is working to help accelerate the adoption of new technologies into the market place in the UK. By bringing together researchers in Universities and industry with real problems to solve we are building up knowledge, putting new teams together and creating a forum for the development of new ideas.

The following represent an introduction to a selection of such alternative cycles. The potential of these alternative technologies to impact the future market will be discussed in more detail in presentations at the Workshop where leading experts will present evaluations of their potential to save carbon.

1. TRIGENERATION

Tri-generation technology is a technology that can provide simultaneously three forms of output energy; electrical power, heating and cooling. Trigeneration is also known as CCHP (Combined Cooling, Heating and Power) or CHRP (Combined Heating, Refrigeration and Power). In essence, trigeneration systems are CHP (Combined Heat and Power) or co-generation systems, integrated with a thermally driven refrigeration system to provide cooling as well as electrical power and heating. CHP systems consist of a power system which can be an internal combustion engine driven by a fossil fuel or a biofuel, an external combustion engine or other thermally or chemically driven systems coupled to a generator which produces electricity. A heat recovery system recovers heat from the power system and exhaust gases to be used for heating applications.

Effective operation of CHP systems requires maximum utilisation of both electrical power and heat. Where there are seasonal variations in heat demand, the utilisation efficiency of CHP systems can be increased if the excess heat is used to power thermally driven refrigeration technologies.

Trigeneration systems have been in operation for many years. Developments in recent years have mainly concentrated on individual subsystems such as the power system, heat recovery system, thermally driven refrigeration machines and system integration and control. With the power system, the main developments has been:

i) improvement of the efficiency of internal combustion engines, particularly gas and diesel engines and the development of engines that can operate with biofuels;
ii) development of microturbines that enable the availability of rejected heat at a much higher temperature than internal combustion engines;
iii) development of fuel cells that offer higher electrical power generation efficiencies than internal combustion engines and microturbines. Progress in thermally driven cooling machines has mainly been on the development of adsorption cooling systems and multi-effect absorption systems to improve

efficiency. Advances in heat transfer and heat exchanger technology now enable the manufacture of more compact heat recovery systems.

Applications
There are a number of examples of application of trigeneration plants in the food industry. The majority of these are large plants in the MW range in food factories where bespoke ammonia absorption plant are linked to gas turbines, or internal combustion engines. More recently, application of trigeneration has been extended to supermarkets with a very small number of installations in the USA, the UK and Japan. These systems are mainly used for space cooling applications and are based on internal combustion engines or microturbines and Li-Br/H2O absorption refrigeration systems. A pilot installation is currently planned in the UK of a system employing an adsorption chiller.

Carbon savings potential
Trigeneration systems can have overall efficiencies as high as 90% compared to 33%-35% for electricity generated in central power plants. However, much of the energy is recovered as heat, which has a much lower value in monetary and carbon terms than electricity. That said, if gas is used to drive CHP and the heat recovered is maximized then carbon emissions are 60% of those displaced from coal fired CHP (Maidment and Tozer, 2001). With use of biofuels and fuel cell technology, significant further carbon savings can be achieved.

2. ELECTROCALORIC COOLING

The **electrocaloric effect** is phenomenon in which a material shows a reversible temperature change under an applied electric field. Electrocaloric materials were the focus of significant scientific interest in the 1960s and 1970s, but were not commercially exploited as the electrocaloric effects were insufficient for practical applications: the highest temperature change achievable being 2.5^{o}C. However, in recent years there has been renewed interest in the field of electrocalorics since the discovery of giant electrocaloric (GEC) effects associated with ferroelectric thin films. GEC was shown to be able to deliver temperature reductions of ~12K (Mischenko et Al. 2006, Neese et Al, 2008)and this opens up the possibilities of using the GEC cycle for practical cooling applications.

Applications
Recent developments in multilayer geometry simultaneously overcomes all the problems previously associated with the practical implementation of this technology. For a commercially available $BaTiO_3$-based multilayer films, it has been possible to show that an ideal GEC heat pump can deliver a cooling power of 22.5 W kg^{-1} but this could be increased via materials optimisation to at least ~2875 W kg^{-1}, such that it has been estimated that a GEC array with a sheet area of just ~0.56 m^2 could deliver ~20 kW cooling power of a typical air-cooled chiller for air-conditioning at residential and commercial sites. Various thin film materials are currently being investigated in order to reduce cost and maximise capacity. Two hurdles to practical implementations are being able to fabricate multilayer GECs of the right material and then to be able to build a fridge around them.

Carbon savings potential
Carbon savings are potentially achievable through improvements in efficiency but also through eliminating refrigerant direct emissions. The efficiency of GEC cooling technology is predicted to be high but this technology is at a very early stage and much, including relative efficiency, is not fully known about this technology.

3.ADSORPTION REFRIGERATION

Adsorption is a heat driven cooling process. It uses an adsorption medium such as activated carbon together with a refrigerant to achieve a cooling effect. It uses a chemical rather than a mechanical compressor and is driven by heat rather than mechanical work. The operation of adsorption heat pumps and refrigerators is based on the ability of porous solids (the adsorbent) to adsorb vapour (the adsorbate or refrigerant) when at low temperature and to desorb it when heated. Although the heating and cooling provided by a single generator is discontinuous, it can be made continuous by operating two or more generators out of phase.

Applications

Numerous possible applications are envisaged for refrigeration, air conditioning and heat pump technology eg: Solar or biomass powered; refrigeration & air conditioning ; Vehicle (mobile) air conditioning; from waste engine heat; Domestic gas fired heat pumps;

Carbon Savings Potential

This technology has the potential to reduce the environmental impact of cooling in numerous ways. Heat powered cycles can make use of renewables or waste heat as well as conventional fuels to reduce CO_2 emissions. Refrigerants used are natural working fluids with low or zero global warming potential.

4. SOLAR POWERED COOLING

Solar powered cooling uses energy from the sun to either drive a vapour compression system via a photovoltaic panel or a sorption chiller driven by heat from solar collectors. There are a number of different of collector/ chiller combinations that have been reported in the literature, including open and closed sorption cycles. The most commonly employed technologies for small to medium scale cooling capacity (< 200 kW) are closed systems such as absorption and adsorption cooling. Open systems like desiccant and evaporative cooling based systems or liquid sorption systems are also in development. The key advantage of solar powered cooling over other renewable cooling based systems is that cooling is often coincident with the load, removing the need to over capacity or energy storage.

Applications

An estimated 450 to 500 solar cooling systems are currently installed worldwide (as at 2008) and four hundred of these installations are in Europe [5]. The market for solar cooling in Europe has increased in the last five years by 50 to 100% as shown in Figure 1.

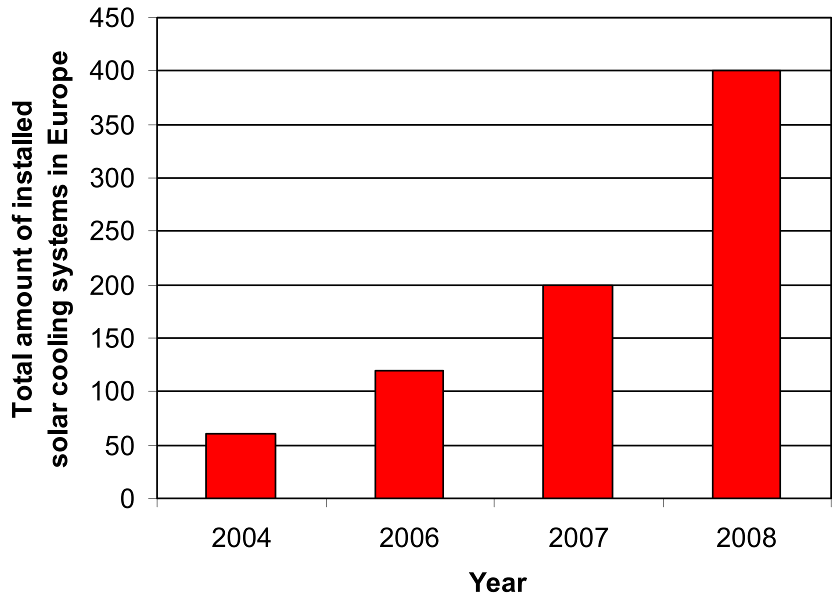

Figure 1: Market development of small to large-scale solar cooling systems in Europe (Sources: Climasol, Fraunhofer ISE, Rococo, Tecsol)

Today absorption chillers with capacities from 10 kW to 500 kW and adsorption chillers with capacities from 7 kW to 15 kW cooling capacity are available on the solar cooling market. Open systems have been proposed for ventilation systems for treating air as they employ a combination of sorptive air dehumidification and evaporative cooling. Single-effect absorption chillers with the working fluid combination of water/lithium bromide or ammonia/water respectively operate over a closed continuous cycle. Ammonia/ water absorption chillers can generate evaporator temperatures down to -60°C, useful for industrial cold processes. Current barriers to application are capital cost, however, with economies of scale, development and greater use of collector technology in other applications, costs will reduce.

Carbon Saving Potential

Sorption chillers use environmentally friendly refrigerants (water or ammonia) and have a low energy demand if the solar energy input can be maximized.

5. MAGNETIC REFRIGERATION

Magnetic refrigeration exploits the magnetocaloric effect (the temperature change observed when certain materials are exposed to a rapidly changing magnetic field) found in for example gadolinium, lanthanum or manganese alloys. As the magnetic elements of the material align in the magnetic field, there is a decrease in entropy, and consequently, the material heats up; when the field is removed it cools down.

The process has been used in cryogenic research since the 1930s (Giauque, 1933) but adjusting the technique to cool large volumes at room temperature is considerably more difficult. `

Applications

Recent breakthrough discoveries of new magnetocaloric materials - LaFeSi (Fujieda et, 2002), MnPFeAs (Tegus et. al, 2002) and CoMnSi (Sandeman et al., 2006) - that are ideally suited for low-cost room temperature operation is reported to start to make the technology feasible.

However, when a magnetocaloric material is exposed to a 1Tesla magnetic field, it changes temperature by ~3º, which is inadequate for any practical application. Recent work has extended the performance to deliver cooling over a 20ºK change in temperature (or span), in a low 1T magnetic field, by implementing a continuous, rapid, active regenerative cooling cycle (United States Patent, 4332135) giving a factor-of-2 improvement in efficiency over an equivalently sized gas compressor (Carbon Trust Grant, 2008). By operating the cooling cycles at high frequency it also enables more cooling per unit mass of coolant, and a consequent reduction in coolant, magnetic field volume and cost.

Carbon Saving Potential

Magnetic refrigeration has several advantages over traditional gas compression technologies. It operates without environmentally harmful gas refrigerants and is up to 50% more efficient (Zimm et al, 1998) than conventional direct expansion refrigeration in the sub-2kW cooling power range (the level of improvements that can be made at higher cooling powers is reduced, as gas compression systems have improving efficiencies at higher cooling powers). This makes the technology ideally suited as both an environmentally friendly and an energy-efficient alternative for domestic and some commercial cooling applications.

6. AIR CYCLE REFRIGERATION

The use of air as a refrigerant provides an environmentally benign refrigerant. It is not flammable, does not suffocate and is food safe. Air cycle is one of the oldest refrigeration technologies and was used widely in at the end of the 18th century. At this point, the technology could not compete with direct expansion refrigerants and due to inefficient components and went out of widespread use in the early 19th century. Today high-speed turbo machinery is available that is compact and lightweight and therefore the use of air as a refrigerant is once again a commercial possibility.

Applications

A number of theoretical studies have indicated the potential for air cycle in food processing operations (Gigiel, Chauveron, and Fitt, 1992; Russell, Gigiel, and James 2000; Russell, Gigiel and James, 2001). Integrated heating and refrigeration is one of the applications with the highest theoretical potential. With conventional vapour compression plant the air temperature must range between ambient and -40°C. With air cycle this range can be substantially increased. In food freezing, lower temperatures will result in faster freezing, improving food quality and either reducing the size of the freezer, or allowing a larger throughput through an existing freezer. Rapid freezing at very low temperatures offers the advantages of rapid heat transfer enabling high quality and value foods. Air temperatures up to 300°C can also be obtained suitable for direct cooking or the production of steam (Evans, Gigiel, Foster and Brown, 2007).

Carbon Saving Potential

Air cycle cooling presents the possibility to save carbon particularly in applications with coincident demand for heating and cooling and in low temperature applications where the COP is relatively high. Also, there will be no direct emissions as air is environmentally benign.

CONCLUSIONS

This paper presents the need to use cooling technologies which save carbon within the RAC sector. Six potential carbon saving technologies are described; trigeneration, adsorption, solar powered cooling, electrocaloric, magnetic and air cycle refrigeration and their application and their carbon saving potential is presented.

Acknowledgements

The paper has been put together with input from Dr Neil Mathur, University of Cambridge; Professsor Savvas Tassou, Brunel University; Ms Judith Evans, London South Bank University; Dr Uli Jakob, Solar Next; Dr Neil Wilson, Camfridge; and Dr Zacharie *Tamainot-Telto* of the University of Warwick.

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