New **refrigeration technologies**

The social dimension of the specific sector of refrigeration and conditioned air production is a crucial one. At stake are economic and sanitation issues, when it is a matter of food conservation, or bacterial growth prevention, or of contributing to comfort in industrialized societies. This sector accounts, in aggregate, for 15% of world electricity consumption, with relevant figures standing at 700-1,000 million refrigerators, and 380 million air-conditioned automobiles worldwide.

Xavier Renauld/Air Liquide

Cold generation is a rising sector, both for industrial and personal uses. Shown here, meat being deep-frozen in the Himalaya™ tunnel.

Refrigeration technologies use refrigerant fluids, and concern a wide range of highly diverse sectors: construction, transportation, food and agriculture, chemicals, and engineering. Cold generation is an area characterized by high energy consumption, and a heavy contribution to releases of **greenhouse gases**.

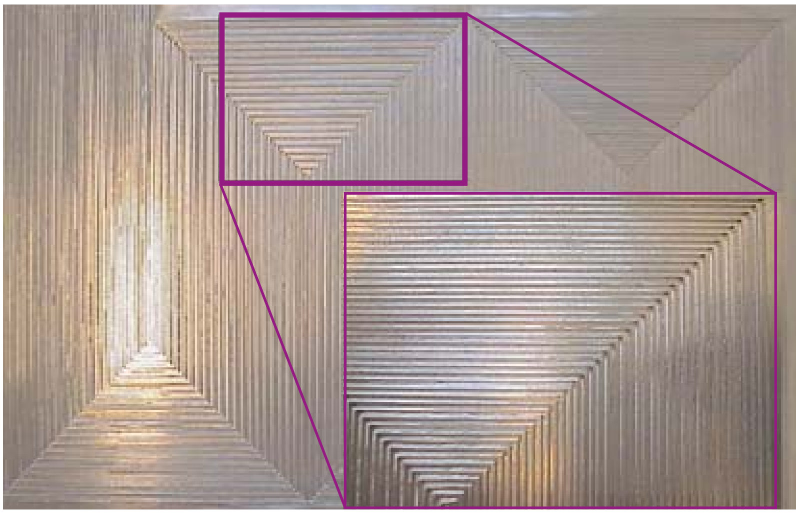
Substitutes for refrigerant fluids contributing to the greenhouse effect

The topic of finding substitutes for **greenhouse-effect** inducing fluids in energy processes, such as are involved in heat pumps and refrigeration equipment, has become a major challenge in the struggle to curb **CO_2** emissions. Refrigerant fluids of the **CFC** type are banned nowadays, however, the fluids selected as substitutes still have an impact on the greenhouse effect that is far from negligible. Thus, the share of global warming of manmade origin relating to chlorofluorides as a whole (**CFCs**, **HCFCs**, **HFCs**, **PFCs**…) stands at over 12%, whereas in terms of quantity such gases amount to less than 100 **ppm**. These figures emphasize the efforts still remaining to be done if amounts of harmful refrigerants are to be restricted, in such devices as heat pumps or refrigeration equipment. Drastic reduction in emissions of refrigerant fluids is unquestionably the driving force for future technological developments, to which CEA is contributing, to meet the requirements of manufacturers. Substituting for such fluids with so-called "natural" fluids does raise, however, for every fluid considered, particular issues, calling for a research effort.

(1) The contribution to the greenhouse effect, for every fluid, is quantitatively assessed by a criterion, its global warming potential (GWP), summing up its warming potential relative to CO_2, to which the datum value 1 is assigned. The HFC-134a fluid used in refrigeration cycles, for instance, has a GWP index of 1,300.

Carbon dioxide: an advantageous refrigerant

CO_2 is a potentially advantageous fluid for energy purposes, while retaining a very low level of contribution to the greenhouse effect [1] - some 1,000 times lower than for a refrigerant of the HFC type. Owing to its specific properties, it exhibits good efficiency when used in a transcritical cycle. [2] It is imperative that technical feasibility of its use be demonstrated, meeting the particular requirements of high pressures, the outcome being a prototype built for a specific application. CO_2, it should be noted, also requires particular attention with respect to gas coolers, owing to unusually high pressures for such systems. Indeed, compressor delivery pressure may reach levels higher than 140 **bars**. Specific investigations are required, to determine sizing correlations for heat exchangers (evaporators, gas coolers). This fluid is being targeted by a major research effort in the automotive sector, with regard to passenger comfort. At the same time, hot water production would also seem to be well suited for this technique.



CEA

Plate condenser developed at GRETh. Improved performance for cold-generation systems involves development of innovative heat exchangers.

Hydrocarbons used as refrigerants

As regards other natural fluids, such as ammonia and **hydrocarbons**, the various hazards associated to their use (toxicity, flammability…) make them tricky to employ. The solution, for use in vapor compression cycles, consists in reducing to a minimum the amounts involved (see Box 1). This requires optimization of the thermodynamic cycle, and the quest for more compact, more efficient heat exchangers. Technological solutions must thus be found to meet this requirement, and a number of avenues are already being considered: **extruded** flat fins, [3] compact plate heat exchangers, minichannel etching technologies… Use of hydrocarbons as refrigerants should expand rapidly, since, as happened with CFCs and HCFCs, an HFC ban may be enforced quite suddenly. In 2005, European companies will indeed be liable for fines, if they exceed their greenhouse gas quotas. [4]

Promising two-phase refrigerants

Cold distribution by means of **two-phase** refrigerant fluids is barely beginning to take off. This topic concerns both cold generation and cold distribution, while restricting use of conventional refrigerants. This involves

(2) A cycle is said to be transcritical when the fluid involved, in this case CO_2, is brought to a pressure higher than its critical pressure by the compressor, then brought down again to a pressure lower than critical pressure by the relief valve.

(3) Extruded flat fin: a kind of flat extruded aluminum plate separating channels.

(4) One quota: one metric tonne carbon dioxide equivalent.

A CEA-designed compression device using hydrocarbons 1

Surprising though it may seem, as regards refrigerant fluids, hydrocarbons are no heavy pollutants, compared to other, commonly used fluids. In effect, the impact of a greenhouse gas is measured in terms of carbon dioxide equivalent release. Whereas one kilogram HFC corresponds to 1,400 kg CO_2 released into the atmosphere, one kilogram propane represents a mere 20 kg CO_2!
GRETh has constructed a compression device using propane as refrigerant. Very little propane - 2 kg only, i.e. six times less than contained in a gas cylinder for domestic use - circulates inside this compression device.
Initial tests show the device exhibits higher thermal power than is the case with a conventional fluid (70 g propane yielding 1 kW cold, as against 240 g HFC fluid for the same yield), and consumes 25% less electricity. It is also fitted with a "spiral" compressor, having the ability to operate at variable speed. It is thus feasible not to operate the device at full capacity at all times, a factor making for possible savings.
The optimization stage for this device, mainly concerning heat exchangers, the key elements in a heat pump, is now being initiated. The sought outcome is to achieve even lower hydrocarbon use, for the same performance.

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Compression device using propane as refrigerant. The device is compact, uses little electricity, and exhibits high thermal power.

insertion of an intermediate refrigerant circuit, between the device making use of the cold, and the refrigeration equipment. Latent-heat [5] operation, to complement sensible-heat [6] functioning, allows good thermal performance levels to be achieved. "Stabilized slurries" represent the most recent breakthrough in this area. These consist in organic gel particulates, filled with a material undergoing phase change at a set temperature, which may lie anywhere in a broad range of temperatures, and suspended in a fluid, serving as carrier (see Box 2). They afford major potentials. However, thermal and flow investigations, together with investigations as to their thermophysical characteristics and storage capacities are research topics that still need to be pursued, before demonstration prototypes can be built.

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(5) Latent heat: the amount of energy transferred through phase change, at constant temperature, for a pure body.

(6) Sensible heat: energy transferred through the sole variation in temperature of a pure body.

Cold distribution by means of "ice slurries" 2

Let us examine the flow regime, in a horizontal pipe, of acrylamide (an organic gel) particles, containing a phase-change material, suspended in a carrier fluid. In the case of a two-phase, liquid-solid fluid, the difference in density between the two phases may result in a particular flow configuration. Since the particles considered are heavier than the carrier fluid, they are subjected to two forces: *gravity*, causing sedimentation, and *lift and drag forces*, which, by contrast, tend to make the flow homogeneous. Flow homogenization depends on velocity. The higher the velocity, the more effective the homogenization. If V stands for the circulation velocity of the two-phase fluid, four main flow regimes are observed.
At very high velocities ($V > V^{***}$), the fluid behaves as a virtually homogeneous fluid (see Figure a). Turbulence favors this process.

Figure a.
Homogeneous flow ($V > V^{***}$).

For $V^{**} < V < V^{***}$, particle distribution is heterogeneous. A particle concentration gradient, linked to the dominant effect of gravity, is observed (see Figure b). The lower the flow rate, the more concentrated the particle distribution becomes in the lower region of the section (for particles heavier than the carrier fluid).

Figure b.
Heterogeneous flow ($V^{**} < V < V^{***}$).

For $V^{*} < V < V^{**}$, particles form a bed, moving at a velocity distinct from that of the carrier liquid (see Figure c). A few particles move through saltation, while others remain suspended in the carrier liquid.

Figure c.
Moving-bed flow ($V^{*} < V < V^{**}$).

For $V < V^{*}$, a large number of stationary particles form a fixed bed (see Figure d). The carrier liquid circulates only in the restricted region available to it. This process causes a rise in pressure losses when velocity drops.

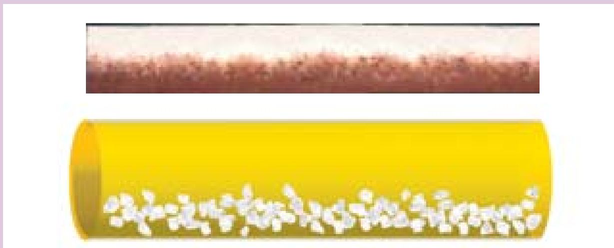

Figure d.
Stationary-bed flow ($V < V^{*}$).

The critical velocity V^{***} thus corresponds to a boundary velocity between homogeneous suspension and heterogeneous suspension conditions. As for velocity V^{**}, this is the boundary velocity for emergence of the drifting process. Values for the various critical velocities depend at the same time on the nature of the particles involved, on the carrier liquid, and on pipe diameter.
The cold distribution process by means of "ice slurries" will be more efficient, to the extent that particles are moved in appropriate fashion by the carrier fluid, not accumulating in any part of the circuit, with no clogging in contractions and no stratification in horizontal pipes.
The findings obtained at CEA are evidence that this type of slurry is a promising concept for cold storage and cold transport applications.

B The greenhouse effect and CO_2

The Sun's energy reaching the ground warms the Earth, and transforms into **infrared radiation**. Just like the panes of a greenhouse – hence the name given to this mechanism – some of the gases present in the atmosphere trap part of this radiation, tending to warm the planet. Thus, in terms of power, the Earth receives, on average, slightly less than 240 **watts**/m². Without the **greenhouse effect**, **mean** temperature on Earth would stand at – 18 °C, and very little water would be present in liquid form. This effect thus has a beneficial influence, since it allows our planet to experience a mean temperature of 15 °C.

However, from the beginning of the industrial era, i.e. for more than a hundred years, humans have been releasing into the atmosphere gases (**carbon dioxide**, **methane**, **nitrogen oxides**, etc.) that artificially augment the greenhouse effect. Since 1750, this increase, with respect to "well-mixed" gases, has amounted to 2.43 W/m². Contributing as it does an "additional radiative forcing" of 1.46 W/m², carbon dioxide (CO_2) accounts for more than half of this "additional greenhouse effect," well ahead of methane (0.48 W/m²), **halocarbons** (chlorofluorocarbons [**CFCs**], hydrochlorofluorocarbons [**HCFCs**], and hydrofluorocarbons [**HFCs**]), accounting for 0.34 W/m², and nitrogen dioxide (0.15 W/m²). Further, the **ozone** in the troposphere exhibits a *positive* radiative forcing of 0.35 W/m² (however, it is estimated that depletion of the stratospheric ozone layer observed between 1979 and 2000 has resulted in a *negative* radiative forcing, of 0.15 W/m²).

This addition to the natural greenhouse effect (155 W/m²) is small, corresponding to an increase of about 1%. Nevertheless, it is practically certain that this has contributed to the rise in mean temperature, for our planet, of about 0.5 °C, observed over the 20th century (see Figure 1). If nothing is done to curb these emissions, carbon dioxide concentration in the atmosphere (see Figure 2) could double by 2100. From current world consumption [1] of **fossil** fuels (7,700 **Mtoe**), the mass of CO_2 currently produced may easily be computed: 20 billion tonnes per year!

This could result in a substantial increase in the greenhouse effect, causing, through nonlinear amplifying effects, profound alterations in climate. Most models predict that doubling the present carbon dioxide concentration would result, by the end of the 21st century, in a rise in temperature of some 2–3 °C. Some models even yield a bracket of 1.5–4.5°C, meaning dramatic consequences could be foreseen for the environment, such as a substantially rising sea level.

Such figures may seem small, entailing only minor consequences for the climate; that, however, is not the case. To understand this point, one should bear in mind that during the "little ice age," from 1450 to 1880, mean temperature only fell, in France, by 1 °C, on average. Some 6,000–8,000 years ago, as Western Europe experienced a war-

(1) European Community, Directorate General for Energy (DG XVII), "Conventional Wisdom" scenario (*European Energy to 2020: A scenario approach*, 1996).

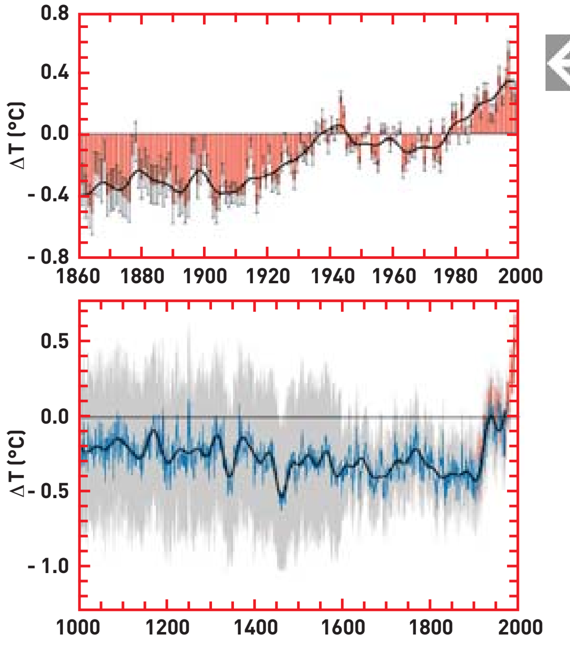

Figure 1. Departures in temperature (ΔT) from the average for the years 1961–1990, over the period 1860–2000, on a global scale (top), and over the past one thousand years in the northern hemisphere (bottom).

B The greenhouse effect and CO_2

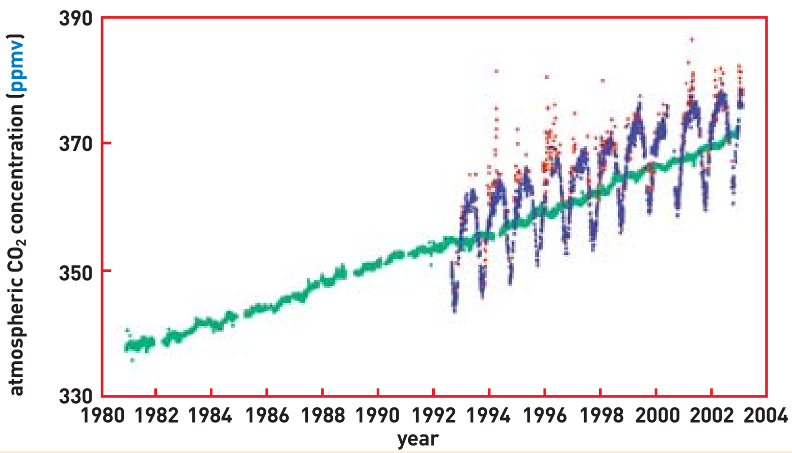

Figure 2.
Evolution of atmospheric CO2 concentration since 1980, as measured on a daily basis by the automatic stations of the Climate and Environmental Science Laboratory (LSCE: Laboratoire des sciences du climat et de l'environnement), since 1981 on Amsterdam Island (Indian Ocean), and since 1992 at Mace Head, on the western coast of Ireland.
Readings on Amsterdam Island (shown in green), well away from any direct perturbation of human origin, essentially evidence the constant rise in concentration. The Mace Head site basically measures oceanic atmosphere (under normal conditions, westerly winds: blue). When wind conditions are reversed, the site receives a continental atmosphere, showing a strong excess in CO^2 (red plots), compared to oceanic atmosphere. Over the mean rise in CO_2 concentration is superimposed a marked seasonal modulation, due to plant vegetative cycle (chlorophyll photosynthesis), plants being CO_2 emitters in winter, and CO_2 absorbers in summer.

mer spell, with a mean temperature 2–3 °C higher than it is today, the Sahara was not a desert, but a region of abundant rainfalls. It is not so much the rise in temperature that gives cause for concern, as its rapid variation (in the course of one century). The large variations previously observed in nature all occurred over much longer timescales, for those at least of a global character. Thus, the last glaciation lasted 100,000 years, and the corresponding deglaciation took 10,000 years. The rapid variation we are currently experiencing may induce major, unexpected perturbations in the climate and the ecosystem, which will not always have time to adapt.

From Rio to Kyoto: the major conferences on the global environment

The evolution of the global environment has led to major conferences being organized, starting in the closing decade of the 20th century.
At the Earth Summit, held in **Rio de Janeiro** (June 1992), the United Nations Framework Convention on Climate Change was signed, this setting the goal of a stabilization of greenhouse gas emissions (this convention came into force on 21 March 1994).
At the Kyoto Conference (December 1997), the protocol was signed providing for a global reduction in emissions of such gases, by an average 5.2% in the period 2008–2012, compared to 1990 levels, for OECD countries and Eastern European countries (including Russia). Reduction targets for the European Union and France are set at 8% and 0% respectively. The ways and means to meet these targets were debated, unsuccessfully, in November 2000 at **The Hague**. Subsequent conferences, held in **Marrakech** (2001), **Johannesburg** (Earth Summit held in August–September 2002), **New Delhi** (October 2002), **Moscow** (September–October 2003), and **Milan** (December 2003) had still not enabled, by 2004, this Kyoto Protocol to be brought into force, until Russia finally decided to ratify the document, at last allowing this enforcement in February 2005.
Under the impetus provided by the United Nations Environment Program (UNEP), the issues raised by substances that deplete the ozone layer in the atmosphere were addressed in **Vienna** (1985), and most importantly in **Montreal** (1987), where the protocol was signed, imposing a reduction in production and use

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The Mace Head monitoring station, Ireland.

of chlorofluorocarbons (CFCs). This protocol was specified by amendments adopted in **London** (1990), imposing a ban on CFCs from 1 January 2000, and extending controls to other compounds (including HCFCs), **Copenhagen** (1992), **Montreal** (1997), and **Beijing** (1999).