Energy efficiency in industry

The requisite of improved energy efficiency and lower capital outlay has led to introduction of compact, high-performance heat exchangers in all industrial processes where heat transfer plays a crucial role. Moreover, in the current economic globalization context, national industries, as in France, need to innovate, to bring to market technologies of high performance, both in economic and technical terms.

Alfa Laval

Optimization of heat transfers in heat exchangers requires development of novel structures and geometries. In this AlfaNova exchanger, wholly made in stainless steel, plate profile is designed to ensure optimum distribution of fluids.

The emergence of new technologies, such as that of compact heat exchangers, only occurs at the outcome of a long process, serving to demonstrate that the new equipment offers better performance than conventional heat exchangers, while process reliability is preserved. Once these stages are completed, the caution of a number of manufacturers still needs to be overcome, to achieve introduction into their production plants.

For that purpose, research and development programs must thus be carried out on three levels. *Basic investigations* seek to achieve improved knowledge of the physics of heat transfer, allowing new structures and geometries to be put forward. *Global investigations* have the aim of validating thermic and hydraulic performance in industrial conditions, this requiring trials on a platform (see Box). Further *investigations*, finally, are needed to integrate the heat exchanger into its production context.

Three interventions carried out by CEA in the area of energy efficiency in industry will be described in this paper. The first one relates to boilers as used in the petrochemical industry; the second concerns gas boilers for apartment blocks; while the third one involves energy savings in glass production processes.

Optimization of boilers for the petrochemical industry

Horizontal-tube boilers are found in many industrial sectors. Their two principal applications are as reboilers, at the base of a distillation column, or evaporators in a refrigeration cycle, mainly as process coolers in the petrochemical industry, and for gas liquefaction. Such boilers have the specific characteristic of involving fairly complex thermic sizing. Indeed, these horizontal-tube boilers are characterized by flow of a liquid-vapor mixture inside the shell, this being governed by natural internal recirculation, which is difficult to **model**. Heat transfer to the tubes outside is strongly dependent on hydrodynamic conditions, resulting in large heat transfer coefficient variability, according to tube position within the bundle.

Sizing methods inadequate for extrapolation to hydrocarbons

A bibliographical survey shows that the correlations used for the sizing of such equipment are based on experiments carried out with refrigerants such as R113 (**CFC**), for example. Consequently, the methods used at present for thermic sizing of equipment functioning with **hydrocarbons** involve a large measure of uncertainty, inasmuch as extrapolation to other fluids is in no way validated.

A major research effort has been carried out by GRETh (1) over the past few years to provide specific information on hydrocarbon boiling in a tube bundle of significant size. Moreover, investigations have enabled answers to be arrived at, concerning improvements resulting from nonsmooth tubes; such tubes are to be gradually introduced into new installations, bringing a very significant performance gain.

Comparison of smooth tubes and improved tubes

The physics of boiling, for a liquid on a hot surface, shows that vapor bubbles initially arise on surface defects, which may be viewed as small cavities, where vapor forms, accumulates and then separates from the wall. The idea of artificially setting up cavities on the surface of a tube, to improve its thermal performance, has thus naturally aroused much interest, for several decades now. Current techniques are highly sophisticated. They allow a tube's surface to be machined and structured, for instance by folding down fins, or through surface deposition of a porous material. Investigations are currently addressing the capacity of an enhanced surface to form a vapor bubble, in other words to activate a nucleation site, and then disengage that vapor so that liquid may come in to take its place, i.e. deactivate the site.

Comparison of heat transfer coefficients for a smooth tube bundle and for a bundle of enhanced tubes, under the same operating conditions, with **isobutane** (see Figure 1), clearly shows that use of enhanced-surface tubes enables a marked rise in heat transfer, throughout the bundle. Improvement is greater than by a factor 3 for low heat fluxes (10 **kW**/m^2), and lies in the range 1.7-3 for high heat fluxes (52 kW/m^2). It should be noted that, when the heat flux is greater than 30 kW/m^2, the heat transfer coefficient tends to reach a plateau around 16 kW/m^2 · K. Such a phenomenon can be explained by vapor saturation of the cavities, liquid then being unable to enter the pores where the vapour lays (see Figure 2). Such results have also been obtained by Professor Manfred Groll and collaborators of Stuttgart University (Germany). In their investigation, using a single tube, they obtained improvement by a factor 3, compared to a smooth tube.


Basell

High-performance horizontal-tube heat exchanger, installed at the Knapsack polypropylene production plant, in Germany. The exchanger is positioned at the base of a distillation column, used for polypropylene purification, the base of the column being charged with **propane**, which is vaporized in the exchanger.

Optimization of a high-temperature heat exchanger for a gas-fired boiler

The European Combo research program is dedicated to development of a new generation of medium-power gas-fired boilers for collective heating (apartment blocks, office buildings, swimming pools, schools…). These new boilers, rated at a nominal power of 400 kW, may be used in cascade, to achieve 4,000 kW power, and improve thermal efficiency.

The objective of this program is to design low-footprint equipment, exhibiting high thermal efficiency (95%, relative to **higher heating value**), and low emis-

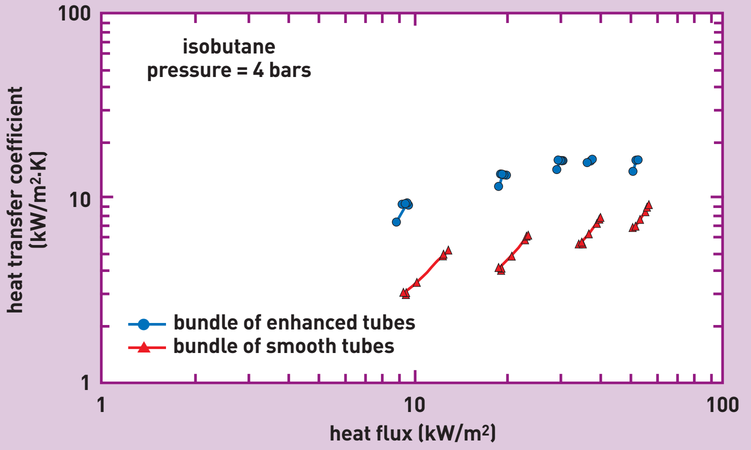
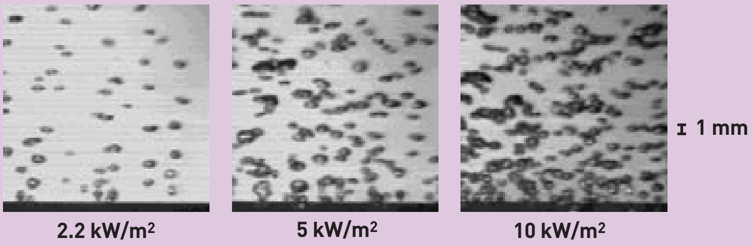


Figure 1.
Heat transfer coefficient, as function of heat flux. Comparison of heat transfer for a smooth tube bundle and a bundle of enhanced tubes, for an inlet liquid flow rate of 46 kg/m^2 · s.



Pr. Manfred Groll *et al.* - IKE

Figure 2.
Increase of the number of nucleation sites with enhanced tubes, as a function of heat flux, for **propane** at saturation temperature of 283 K.

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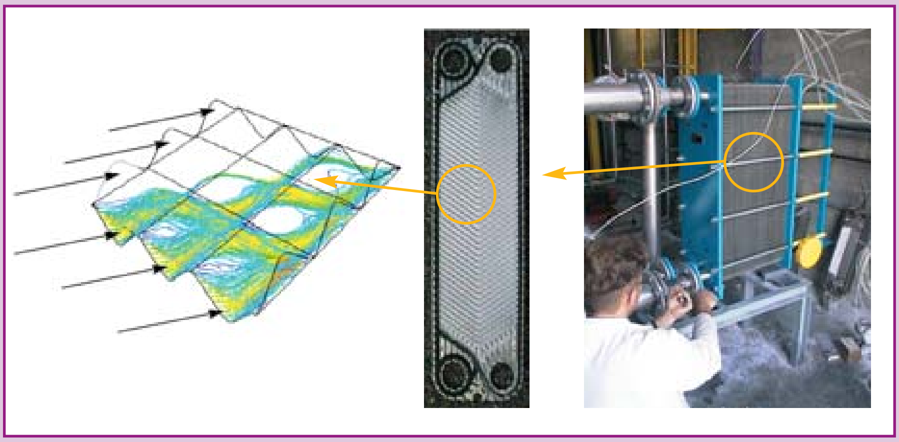
(1) This acronym effectively refers, in this case, both to CEA's Multi-Energy Systems and Energy Management Service (Grethe), and to the Research Group on Heat Exchangers (GRETh: Groupement pour la recherche sur les échangeurs thermiques) proper (see Box on *Modeling flows*).

The Esther Platform

In GREThʼs remit, research and development work concerning innovative heat exchangers plays an essential part. Owing to its position, at the interface between upstream research and competitive industrial research, GRETh has availed itself of a platform having the capability to meet its R&D requirements: the Esther Platform. This is dedicated to heat exchanger development, from millimeter scale to pilot for industrial and nuclear applications.

The Esther Platform makes tools available at a variety of levels. On the *local scale*, the tools of the software platform (see Box on *Modeling flows*) are provided, affording the ability to analyze local thermalhydraulics processes within the exchanger, typically on the scale of a few fins. These have enabled, in particular, optimization of fins for compact heat exchangers, of insert shapes for glass furnaces…


CEA

From local scale to industrial heat exchanger: plate heat exchanger.

On the *elementary channel scale*, analytical trial loops have been put in place. On the basis of sensitive instrumentation (void fraction probe, microsensors, hot-cold wires, infrared cameras), it is feasible to secure both local and global experimental data on the scale of the elementary channel, typically an exchanger plate. Such data, a requisite as they are for numerical modeling, lead to a better understanding of physical processes, with a view to optimization.

On the *pilot scale*, semi-industrial loops enable testing of actual-size heat exchangers, in representative conditions. Thus, GRETh can avail itself of a full range of loops. A number of these are dedicated to evaporation or condensation of hydrocarbons or alcohol, for the industrial refrigeration sector, and the chemical and petrochemical industry. Some are dedicated to high-temperature gas flows (up to 550 °C in 2004, 850 °C in 2005) for cogeneration and HTR nuclear reactor development work. Others are used for solid particulate-charged flows, for the purposes of fouling-defouling and filtration investigations. GRETh further operates an exchanger-reactor test loop.

At the beginning of 2004, as part of the new energy technologies effort, the Esther Platform was fitted with a new compact reformer test loop, for the purposes of investigations on hydrogen production from liquid hydrocarbons.

Thus, GRETh has on call, in a single location, all the tools required for technological innovation, from the elementary scale right up to industrial pilot.

The balance sheet for 2003 speaks for itself. The Esther heat exchanger development platform enabled, on the one hand, a patent to be applied for concerning a novel compact exchanger geometry, and, on the other, reliability to be achieved for Haricot chevron plates (joint CEA-Alfa Laval patent); and, finally, the setting up of a number of joint heat-exchanger development programs, involving recognized protagonists on the international scene.

The platformʼs success stems from the variety of tools available, but equally from the strong synergy prevailing between PhD graduate researchers, technicians and engineers working with the selfsame purpose: optimization of energy efficiency in thermal systems.

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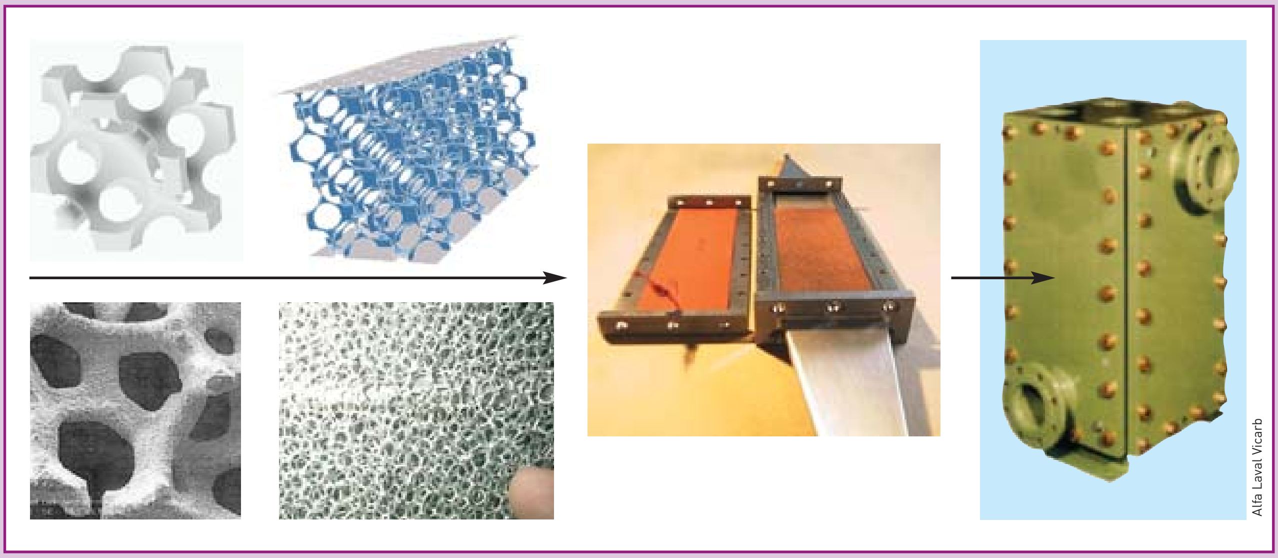
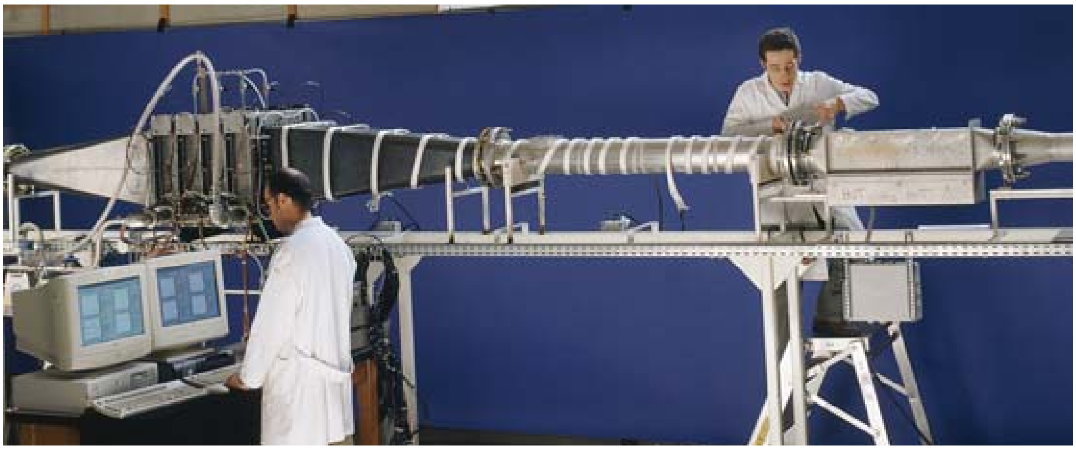


CEA

From local scale to industrial heat exchanger: metal-foam heat exchanger.


A. Gonin/CEA

Combo gas-fired boiler development program, for which CEA is investigating the heat-recovery component. Shown here, the exchanger scale model undergoing tests.

sion rate for pollutants, principally of the nitrogen oxide (**NOx**) type (less than 20 mg per kilowatt-hour [**kWh**] generated). These goals are to be achieved through use of radiant burners, and condensation of the water held in combustion products from **natural gas**. While condensation boilers (2) are fairly widespread on the domestic market, this concept is still fairly undeveloped for higher power outputs.

Participants in the program include boiler and component manufacturers, gas utilities, and research centers and universities.

Innovations

The first innovative point, in this program, is the use of radiant burners. These burners are made from a porous material (metal fibers, or ceramic foam), allowing short and low-temperature flames, these remaining inside the porous matrix. Whereas for a conventional burner flame color is blue, in radiant mode color takes on a red-orange hue, corresponding to surface temperature for the porous structure. In such conditions, a non negligible ratio of heat transfer (some 20%) is made by radiation to surrounding surfaces.

This characteristic obliges us to modify the design of the heat exchanger standing in front of the burner, in order to be efficient for both transfer modes: **convection** and radiation.

Heat exchanger design and sizing

GRETh carried out numerical simulations and trials to achieve optimum sizing for the new heat exchanger. Two aspects must thus be taken on board: heat transfer by radiation between the burner and the front rows of tubes of the heat exchanger, and convective transfer for following rows.

As regards to radiation, optimization was achieved with respect to tube positioning, and influence of the presence of fins or otherwise. The investigation showed that a front row of tubes, packed very close together and positioned at a short distance from the burner, allows best efficiency for radiative heat transfer. High emissivity must further be ensured for tube surfaces, which can be achieved through appropriate surface treatment. Presence of fins, regardless of their shape and size, only results in very limited gains in radiation efficiency - less than 5%. The option selected thus comprises a first row of smooth tubes, fairly closely spaced, while leaving sufficient passage for gas, and located close to the burner, this being feasible in radiant mode with no external flame.

For convective transfer, tubes with large fins are used. These exhibit a large heat transfer surface, compensating for the rapid falling of gas temperature. Experiments with air, on a complete prototype heat exchanger, allowing detailed instrumentation, were carried out at GRETh to characterize tube thermal performance, in terms of heat transfer and fin efficiency.

Three-dimensional analysis of thermal behavior

Three-dimensional simulations of the heat exchanger's performance were carried out by GRETh, using the FLUENT software. Taking into account both heat transfer modes (radiation and convection), these enabled a good understanding of overall and local exchanger thermal behavior (including instabilities and edge effects). It was also possible to look for solutions to improve its performance (see Figure 3).

These simulations (physical models and boundary conditions) were validated through comparisons with measurements performed on the prototype boiler. Their outcome will be used to test future ideas for heat exchanger improvements, with a good confidence in the results.

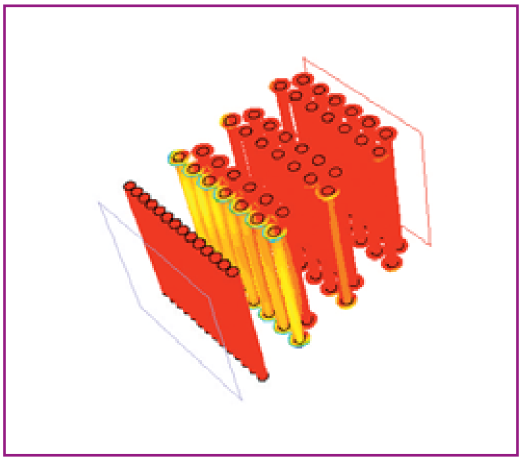

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Figure 3.
Geometry used in numerical simulations carried out at GRETh: a front row of smooth tubes, closely packed together, followed by 6 rows of finned tubes.

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(2) Combustion of natural gas yields to steam. In a condensation boiler, the heat contained in this steam is recovered, by contrast to a conventional boiler where it is rejected outside the building. For that purpose, gases pass through an exchanger-condenser, in which vapour condenses, allowing additional heat recovery. The resulting water is rejected to the wastewater circuit.

At the same time, in order to design a more compact boiler, implementation of a different technology, namely a plate and fin heat exchanger, is presently under development. This type of exchanger will afford the ability to achieve a very high transfer-area-to-overall-volume ratio, while improving heat transfer coefficients.

Optimization of glass furnace regenerators

For many years now, GRETh has been working in collaboration with the research and design center (CREE) of the Saint-Gobain Group's ceramics branch, on optimization of glass furnace regenerator stacking. Over the past three years, this research program has centered on PhD research funded under the CIFRE scheme,(3) this being presented in December 2003. The aim of this work was to improve glass furnace energy efficiency, by designing new regenerator geometries.

The solid matrix: the key component

A major proportion of glass furnaces, so-called *flame furnaces*, operate by using **fossil energy**. The energy required to fuse the glass is transmitted by radiation from the flame (gas or fuel oil combustion) to the glass batch. Only a small part of available energy is thus directly used. The energy contained in the hot gases would thus be wasted, without the installation of regenerators, allowing also to preheat the air required for combustion. Regenerators have been in use in glassmaking since the 19th century, and, owing to their steady improvement, still represent a high-performance solution, this being due in particular to the high preheating temperatures achieved.

The operating principle of an exchanger-regenerator involves alternate circulation of two fluids, a hot fluid, then a cold fluid, over a solid matrix used to store and release energy. Regenerators are always used in pairs, to allow continuous furnace operation.

Regenerator efficiency depends on the optimization of the solid matrix it contains. French company SEPR (Société européenne des produits réfractaires), a Saint-Gobain Group subsidiary, manufactures and supplies regeneration stacks based on cruciform components. The hot and cold fluid circulates alternatively in the channels formed by these components of different sizes and configurations according to the type involved. Heat transfer between the cold and hot fluids and stack components is done by convection or heat radiation processes.

Saint-Gobain SEFPRO

Cruciform components manufactured by SEPR Corporation. Shape, size, and materials involved vary widely.

Numerical simulation and tests for better-performing stacks

Research work carried out at GRETh, on the basis of a detailed investigation of the physical processes involved, was the use of experimental and numerical resources, to develop novel, better-performing stack configurations.

As regards experimental resources, GRETh relied on an experimental device composed of two regenerators on a near-industrial scale (with a height of 5 meters), operating in actual thermal alternate conditions (heat storage-release). All temperature measurement devices placed inside the regenerators enable a better understanding and the quantitative evaluation of heat transfer mechanisms in the different stack components.

Saint-Gobain SEFPRO

Experimental installation with two regenerators of 5-m height, enabling investigation of thermal behavior of cruciform components, thus allowing optimization of stack configurations.

Numerical simulation is used as a tool to complement trials, affording as it does the ability to investigate easily geometric configurations that do not exist as yet. For the FLUENT software, the selection of appropriate models adapted to the particular operating conditions for the stacks (large vertical temperature variations) was first validated through comparison with measurements obtained from the experimental installation. Subsequently, parametric investigations allowed confirmation of the benefit of modifications made to the stacks, by testing their incidence on convective heat transfers.

Outcome of this investigation was the development of new cruciform components, and novel stack geometries.

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(3) CIFRE: *convention industrielle de formation par la recherche* - a French government-funded scheme to support PhD-level technological R&D work in industry.

A The many states of energy

"Nothing lost, nothing created," as Lavoisier, the father of modern chemistry, wrote in his day. This motto, true as it is of chemical species, applies equally to energy. Indeed, energy is a multifarious entity, which may transform into highly diverse aspects. However, the primary energies that may be directly accessed in nature are limited in number: such are fossil energies (coal, oil, natural gas), **nuclear energy**, and renewable energies (hydro energy, biomass energy, solar energy, wind energy, geothermal energy, tidal energy). These primary energies are the constituents of what is known as the ***primary energy mix*** (see Figure 1).

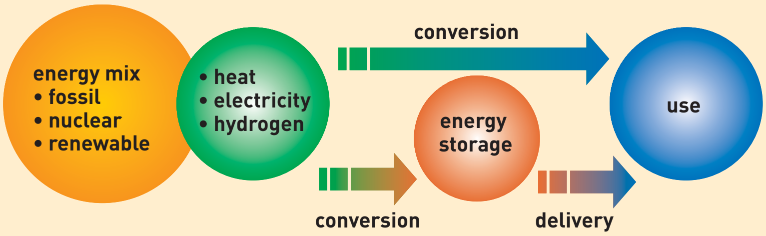


Figure 1.
The energy scheme.

For most applications, energy must be **converted** to make it compatible with the use under consideration. Of course, nature, highly ingenious as it is, devised the very first energy converters, namely living beings. Plants, through photosynthesis, effect the conversion of radiant light energy into chemical energy. The human body itself allows, in particular, the conversion of chemical energy into mechanical energy, by way of the muscular system. Subsequently, humans went on to invent large numbers of converters (see Figure 2). The first such converter, chronologically, is quite simply fire, converting chemical energy (combustion) into light, and heat. Of more recent origin, a television set carries out conversion of electricity into light energy (pictures) and mechanical energy (sounds). In fact, many energy systems involve a combination of a number of converters, as e.g. a nuclear power station, effecting as it does the conversion of nuclear energy into thermal energy (reactor), then into mechanical energy (turbine), finally through to electric energy (alternator). Unfortunately, the second principle of thermodynamics tells us that any energy transformation carries a cost: a more or less extensive portion of the energy involved is dissipated in the form of unusable heat (through friction in a mechanical system, for instance). In the case of a present-generation nuclear power station, the electric energy generated only amounts to one third of the nuclear energy initially contained in the fuel.

Of course, matters would be altogether too simple, however, if energy could be consumed as and when it is generated, on the very site where it is produced. In very many cases, energy-consuming sites may be far removed from the production site, production and concomitant demand, moreover, not always being matched (as with photovoltaic electricity in nighttime, for instance). Sound energy management thus requires deployment both of an **energy distribution network**, and of **energy storage** capabilities.

Energy transport is effected by means of an energy carrier. Currently, the two main such carriers are **electricity**, and **heat**. Tomorrow, however, a new carrier may become dominant: hydrogen, this being converted into electricity and heat by means of fuel cells.

Finally, if energy is to be available at all times, it is essential that there should be the ability to store it: to "get it in a can," so to speak. Such **storage** may take a variety of forms. Energy may be stored in **mechanical** form (*potential energy*, in the case of the water reservoir of a hydroelectric dam, or *kinetic energy*, in the case of a flywheel), or in **thermal** (hot-water tank), **chemical** (gasoline tank, primary and storage batteries), or even magnetic (superconducting coil) form.

Energy management is thus a complex, involved craft, combining production, transformation, transport, and storage. In the current context of energy debate, it is becoming increasingly apparent that, tomorrow, energy networks will grow in size and number, in accordance with a multimodal approach (concurrent management of a number of networks combining diversified energy sources). **New energy technologies** are thus bound to play an essential part in these developments.

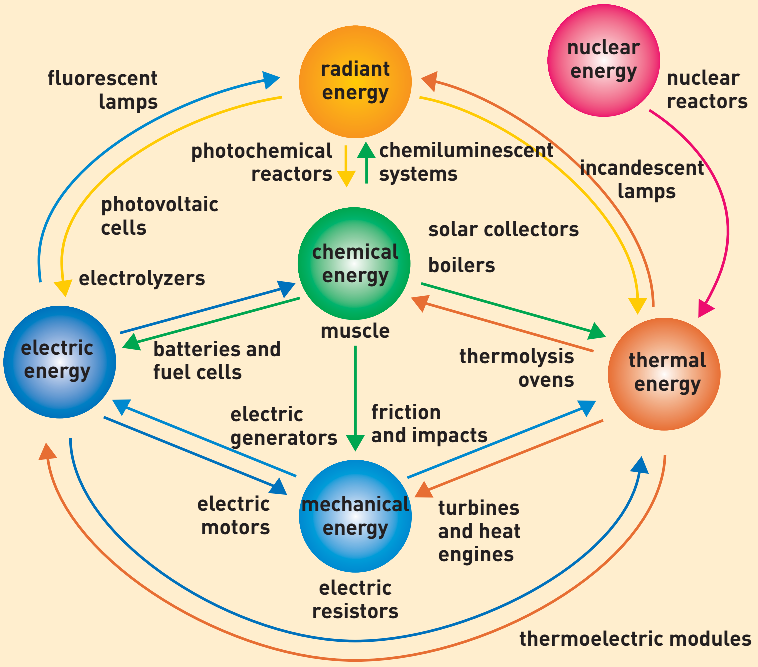
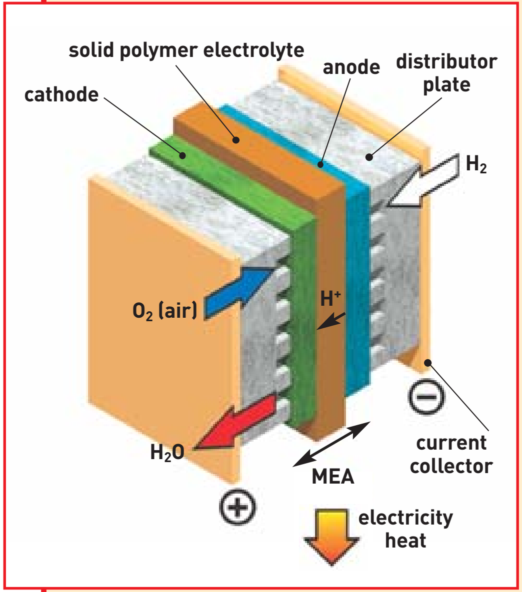


Figure 2.
Conversions of the six main forms of energy, with a few examples of energy converters.

C

How does a fuel cell work?



Operating principle of the fuel cell: the example of the proton-exchange membrane fuel cell. MEA stands for membrane-electrode assembly.

The fuel cell is based on a principle discovered quite some time ago, since it was in 1839 that Sir William Grove constructed the first electrochemical cell working with hydrogen as its fuel, thus demonstrating the ability to generate electric current through direct conversion of the fuel's chemical energy. Since the fuel cell has the special characteristic of using two gases - hydrogen H_2 and oxygen O_2 - as its electrochemical couple, the oxidation-reduction reactions occurring inside the fuel cell are particularly simple.

The reaction takes place inside a structure (the basic electrochemical cell), consisting essentially in two electrodes (the anode and cathode), separated by an electrolyte, i.e. a material that lets ions through. The electrodes employ catalysts, to activate, on the one side, the hydrogen oxidation reaction, and, on the other, the oxygen reduction reaction.

In the case of an acid-electrolyte cell (or proton exchange membrane fuel cell), the hydrogen at the anode is dissociated into protons (or hydrogen ions H^+) and electrons, in accordance with the oxidation reaction: $H_2 \rightarrow 2\ H^+ + 2\ e^-$. At the cathode, the oxygen, the electrons and the protons recombine to yield water: $2\ H^+ + 1/2\ O_2 + 2\ e^- \rightarrow H_2O$. The principle of the fuel cell is thus the converse of that of water electrolysis. The thermodynamic potential for such an electrochemical cell, consequently, stands at around 1.23 volt (V). However, in practice, the cell exhibits a voltage of about 0.6 V for current densities of 0.6-0.8 A/cm^2. The efficiency of such a fuel cell is thus equal to about 50%, the energy dissipated naturally being so dissipated in the form of heat.

E Storage batteries, cells and batteries: constantly improving performance

Storage batteries – also known as accumulators, or secondary **batteries** – and batteries – so-called primary batteries – are electrochemical systems used to store energy. They deliver, in the form of electric energy, expressed in watt–hours (**Wh**), the chemical energy generated by electrochemical reactions. These reactions are set in train inside a basic cell, between two **electrodes** plunged in an **electrolyte**, when a load, an electric motor, for instance, is connected to its terminals. Storage batteries are based on reversible electrochemical systems. They are rechargeable, by contrast to (primary) batteries, which are not. The term "battery" may further be used more specifically to denote an assembly of basic cells (whether rechargeable or not).

A storage battery, whichever technology is implemented, is essentially defined by three quantities. Its **gravimetric** (or **volumetric**) **energy density**, expressed in watt–hours per kilogram (Wh/kg) (or in watt–hours per liter [Wh/l]), corresponds to the amount of energy stored per unit mass (or per unit volume) of battery. Its **gravimetric power density**, expressed in watts per kilogram (W/kg), measures the amount of power (electric energy delivered per unit time) a unit mass of battery can deliver. Its **cyclability**, expressed as a number of cycles, (1) characterizes storage battery life, i.e. the number of times the battery can deliver an energy level higher than 80% of its nominal energy; this quantity is the one most frequently considered for portable applications.

Up to the late 1980s, the two main technologies prevalent on the market were lead–acid storage batteries (for vehicle start-up, backup power for telephone exchanges...), and nickel–cadmium storage batteries (portable tools, toys, emergency lighting...). Lead–acid technology, more widely referred to as lead–acid batteries, or lead batteries, is also denoted as lead–acid systems. Indeed, the chemical reactions employed involve lead oxide, forming the positive electrode (improperly termed the cathode), and lead from the negative electrode (anode), both plunged in a sulfuric acid solution forming the electrolyte. These reactions tend to convert the lead and lead oxide into lead sulfate, further yielding water. To recharge the battery, these reactions must be reversed, through circulation of a forced current. The disadvantages found with lead–acid technology (weight, fragility, use of a corrosive liquid) resulted in the development of alkaline storage batteries, of higher capacity (amount of energy delivered during discharge), yielding however a lower electromotive force (potential difference between the system's terminals, under open circuit conditions). Electrodes for these systems are either based on nickel and cadmium (nickel–cadmium storage batteries), or nickel oxide and zinc (nickel–zinc storage batteries), or silver oxide coupled to zinc, cadmium, or iron (silver-oxide storage batteries). All these technologies use a potassium hydroxide solution as electrolyte. Lead–acid technologies, as indeed alkaline batteries, are characterized by high reliability, however gravimetric energy densities remain low (30 Wh/kg for lead–acid, 50 Wh/kg for nickel–cadmium).

In the early 1990s, with the growth in the portable device market, two new technological pathways emerged: nickel–metal hydride storage batteries, and lithium storage batteries (see Box on *Operating principle of a lithium storage battery*). The first-mentioned pathway, involving a nickel-based positive electrode and a negative electrode – made of a hydrogen-absorbing alloy – plunged in a concentrated potassium hydroxide solution, allowed gravimetric energy densities of 70–80 Wh/kg to be achieved. The second pathway had already been targeted by research around the late 1970s, with a view to finding electrochemical couples exhibiting better performance than the lead–acid or nickel–cadmium storage batteries used up to that point. Initial models were thus designed around a metallic-lithium-based negative electrode (lithium-metal pathway). However, that technology was faced with issues arising from poor reconstitution of the lithium negative electrode, over successive charging operations. As a result, around the early 1990s, research was initiated on a new, carbon-based type of negative electrode, this serving as a lithium-insertion compound. The lithium-ion pathway was born. Japanese manufacturers soon made their mark as leaders in the field. Already in business as portable device manufacturers, they saw the energy source as numbering among the strategic components for such devices. Thus it was that Sony, not initially involved in battery manufacture, decided, in the 1980s, to devote considerable resources to advance the technology, and make it suitable for industrialization. In February 1992, Sony announced, to general stupefaction, the immediate launching of industrial production of lithium-ion storage batteries. These early storage batteries exhibited limited performance (90 Wh/kg). Since then, these batteries have seen notable improvement (from 160 Wh/kg to over 180 Wh/kg in 2004), owing, on the one hand, to the technological advances made (reduction in the unproductive fraction of battery weight and volume), and, on the other, to optimization of materials performance. Gravimetric energy densities of over 200 Wh/kg are expected around 2005.

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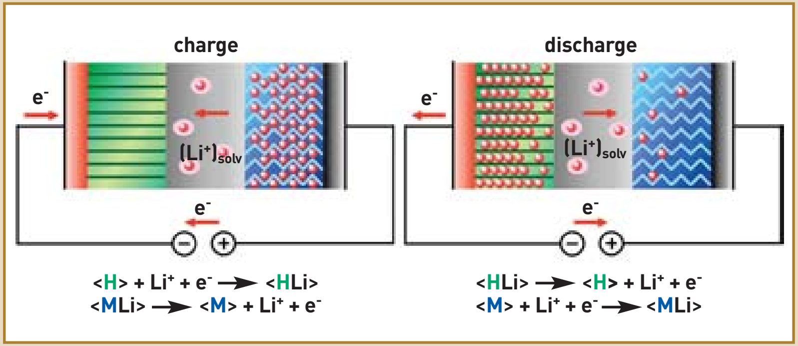
(1) One cycle includes one charge and one discharge.

Operating principle of a lithium storage battery



During use, hence during discharge of the storage battery, lithium released by the negative electrode (<H>: host intercalation material) in ion form (Li^+) migrates through the ion-conducting electrolyte to intercalate into the positive electrode active material (<MLi>: lithium-insertion compound of the metal oxide type). Every Li^+ ion passing through the storage battery's internal circuit is exactly compensated for by an electron passing through its external circuit, thus generating a current. The gravimetric energy density yielded by these reactions is proportional both to the difference in potential between the two electrodes, and the quantity of lithium intercalating into the insertion material. It is further inversely proportional to system total mass. Now lithium is at the same time the lightest (molar atomic mass: 6.94 g), and the most highly reducing of metals: electrochemical systems using it may thus achieve voltages of 4 V, as against 1.5 V for other systems. This allows lithium batteries to deliver the highest gravimetric and volumetric energy densities (typically over 160 Wh/kg, and 400 Wh/l), 50% greater, on average, than those of conventional batteries. The operating principle of a lithium storage battery remains the same, whether a lithium-metal or carbon-based negative electrode is employed. In the latter case, the technological pathway is identified as lithium-ion, since lithium is never present in metal form in the battery, rather passing back and forth between the two lithium-insertion compounds contained in the positive and negative electrodes, at every charge or discharge of the battery.

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/m^2. 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.

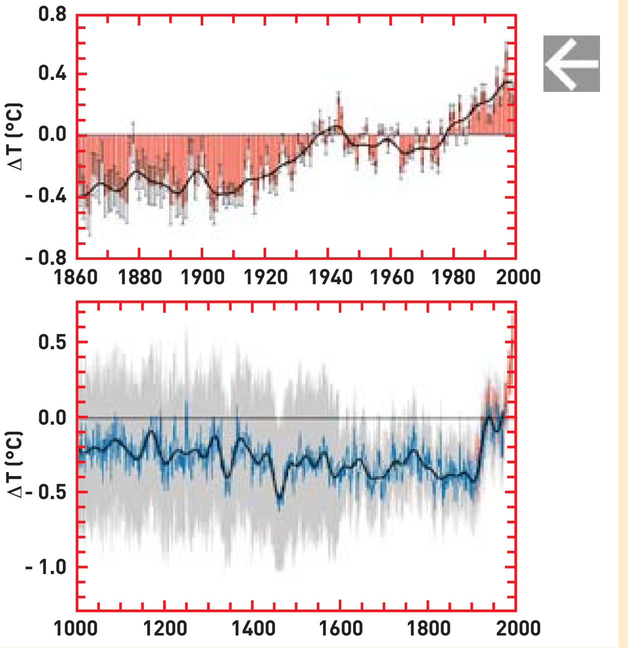
However, from the beginning of the industrial era, i.e. for more than a hundred years, humans have been releasing into the atmosphere gases (carbon dioxide, methane, nitrogen oxides, etc.) that artificially augment the greenhouse effect. Since 1750, this increase, with respect to "well-mixed" gases, has amounted to 2.43 W/m^2. Contributing as it does an "additional radiative forcing" of 1.46 W/m^2, carbon dioxide (CO_2) accounts for more than half of this "additional greenhouse effect," well ahead of methane (0.48 W/m^2), halocarbons (chlorofluorocarbons [CFCs], hydrochlorofluorocarbons [HCFCs], and hydrofluorocarbons [HFCs]), accounting for 0.34 W/m^2, and nitrogen dioxide (0.15 W/m^2). Further, the ozone in the troposphere exhibits a *positive* radiative forcing of 0.35 W/m^2 (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/m^2).

This addition to the natural greenhouse effect (155 W/m^2) 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-

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).



🟥 thermometer readings
🟦 estimated data

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

B The greenhouse effect and CO$_2$

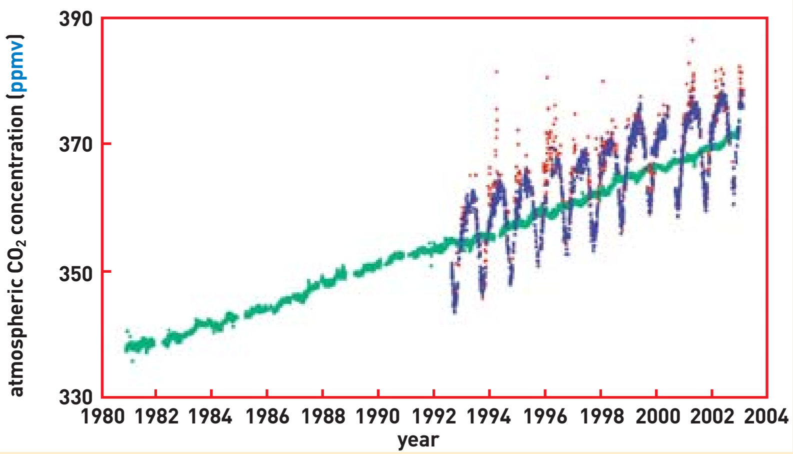

Figure 2.
Evolution of atmospheric CO2 concentration since 1980, as measured on a daily basis by the automatic stations of the Climate and Environmental Science Laboratory (LSCE: Laboratoire des sciences du climat et de l'environnement), since 1981 on Amsterdam Island (Indian Ocean), and since 1992 at 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 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).


National University of Ireland

The Mace Head monitoring station, Ireland.

Modeling flows

In the area of heat exchangers, accurate understanding of flow has become a critical factor, with respect to design and optimization. Indeed, making flow **turbulent**, or turning it into a **two-phase** flow, is the best way to increase heat transfer between a fluid and a wall. That is why such complex flow is to be found in most industrial processes. For instance, in the case of compact heat exchangers, the fluctuating, three-dimensional, broad-energy-spectrum characteristics of turbulence are sought for, to optimize performance. However, these three aspects mean experimental measurements are difficult, and generalization of physical models is not readily achievable. Up to 5 years ago or thereabouts, use of numerical methods, for the analysis of this type of flow, was the preserve of highly skilled, well-versed scientists and research workers, and was often restricted to simple geometries. Over the past few years, growth in computer resources, and dissemination of fluid-mechanics computation programs, have resulted in numerical **modeling** now being available to all. Such methods are opening up a new field of investigation, by offering a major leap in our ability to predict heat transfers. Nevertheless, the gap remains great, between academic investigations, and industrial reality. Intensive validations, in particular, affected on realistic industrial problems, are still lacking.

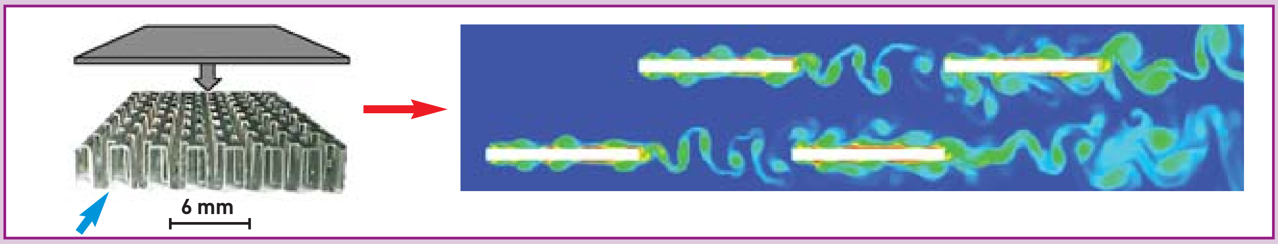

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Figure 1.
Snapshot of the air-temperature field at a given time in a compact heat exchanger, obtained with the Trio_U software. The gray plate corresponds to one of the plates positioned on either side of the fins, forming a channel. The blue arrow stands for the flow perpendicular to the fins, this being shown in the figure at right as a flow from left to right; the image shows a horizontal section at half fin height.

Faced with this situation, work carried out by GRETh follows a twofold thrust. This involves, on the one hand, effecting industrial validation of advanced thermal simulation models, on the basis of heat exchanger-related problems, and, on the other, making such models, and their domains of validity, available to GRETh's manufacturers' club, through the software platform concept.

GRETh (Groupement pour la recherche sur les échangeurs thermiques: Research Group on Heat Exchangers), registered as a non-profit organization under French law, has the remit of disseminating scientific and technological findings from research work carried out in the area of heat exchangers, and enable value-added applications of its findings in industry. For that purpose, the GRETh Manufacturers' Club can call on support from laboratories at CEA (**Grethe**: Service Système multi-énergies et gestion de l'énergie - Multi-Energy Systems and Energy Management Service), CNRS, and academe (LEGI: Laboratoire des écoulements géophysiques et industriels - Geophysical and Industrial Flow Laboratory), with privileged connections with thermics technical education centers, such as the Thermics and Energy Engineering University Technological Institute at Grenoble. The organization has opened itself to Europe, in particular by acting as coordinator to put in place the European SHERHPA (Sustainable Heat and Energy Research for Heat Pump Applications) Program.

By way of illustration of this activity, mention should be made of fundamental work, carried out with assistance from **Ademe**, on the investigation of turbulent flow in compact heat exchangers. (1) By carrying through a systematic survey of the implementation of a variety of turbulence models and programs such as CEA's Trio_U, FLUENT, and STAR-CD, (2) it was shown, through comparison with experimental findings, that, through discerning use of advanced turbulence models, of the LES (3) type, it became feasible to have at hand a reliable preliminary sizing and optimization tool, for compact heat exchangers (see Figure 1 and Figure 2). A best-practice guide, intended for participants in the GRETh club, was drawn up, to specify the best way of approach for a modeling problem, concerning industrial turbulent flows. To follow up this activity, GRETh initiated in 2004 work on the modeling of two-phase industrial flows, in collaboration with thermalhydraulics teams from CEA's Nuclear Energy Division (CEA/DEN).

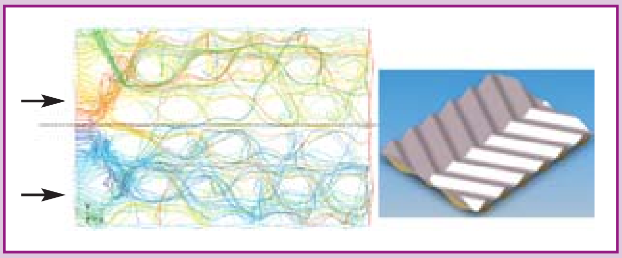

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Figure 2.
Image of a fluid flow in a plate and frame heat exchanger, obtained with the FLUENT software. In the example investigated here, chevron pitch is about 10 mm. Arrows show the direction of flow.

Making such methods available to manufacturers is equally a concern at GRETh. This involves working in collaboration with an industrial partner, giving him access to available resources, and closely involving him in tool implementation. Manufacturers who call on GRETh for breakthrough technological developments are well aware of the benefit accruing from association with a laboratory that endeavors to go beyond mere demonstration of the potentials of these new methods.

> Patrice Tochon
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CEA Grenoble Center

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(1) PhD dissertation presented by F. Michel in late 2003.

(2) FLUENT and STAR-CD: these are computational fluid dynamics programs, marketed by Fluent and CD-adapco Group respectively.

(3) LES (large eddy simulation): large-scale simulation, a promising technique for the prediction and analysis of turbulent flows. By contrast to direct simulation, representing as it does all scales with no approximation involved, this relies on scale separation. Thus, scales of a magnitude greater than an arbitrary value are directly determined by computation, whereas other scales are taken into consideration by way of a statistical model, known as a subgrid model.