Bringing Heron into the present

Turbo power can help the environment

Dr.-Ing. Hartmut Krain

Centrifugal compressor used in DLR testing: Stage pressure ratio 6:1, peripheral speed 2,100 km/h

The environment has become a major topic of discussion in the public arena. It may come as a surprise to some that many of the current environmental issues can be addressed using conventional technologies – technologies such as turbomachinery. DLR has invested a considerable amount of research into this technology.

Turbo machines play an important part in our everyday existence. We encounter them in the form of turbines that are used for energy generation as well as in the form of compressors for energy conversion – for example to pressurise and propel gases. Both types of turbo machines are equipped with rotating blade wheels inserted into a continual gas flow, either adding energy (compressor) or extracting it (turbine). These processes are based on the laws of fluid dynamics.

One of the first documented mechanical devices to take advantage of these laws came from Heron of Alexandria in 60 AD. The Greek scholar proposed a spherical steam turbine based on the rocket principle. Water is heated in the basin that the turbine is mounted on, and thus turns into steam. This steam is directed into the sphere via one of the two mounting pipes. Two jet nozzles are mounted on either side of the sphere, curved in opposing directions. These propel the sphere as the steam is expelled. Heron also described another device, which was powered by hot air instead of steam. This was one of the first documented gas turbine systems, and was theoretically suitable for generating energy. In practice, however, the generated energy merely compensated for the friction loss. Any exploitation of the effective power – for example, to drive a generator or fan – was not yet a conceptual reality.

The Romans were the first to realise the practical uses of the turbo machines. Around 100–200 AD, they constructed water wheels to grind grain. In around 1500 AD, Leonardo da Vinci completed a drawing of a rotor, suspended in a chimney that was propelled by the hot, rising gases. These types of machines were initially designed simply through observation and without any knowledge of aerodynamic laws. It wasn't until 1750 that Leonard and Albert Euler analysed Heron's steam turbine and conducted a series of seminal tests, which in 1754 led to the formulation of the "Euler turbine equation". This became the foundation of turbomachinery as we know it today.

The turbo principle is old – the demand on the compressors is new

Although modern gas turbines look very different from Heron's gas turbine, they are based on the same principles: A gaseous substance is pressurised (compressor), heated through external energy (combustion chamber), and then expanded (turbine). The turbine's power output is distributed. Part of the output is used to power the compressor; the remaining effective power is used to drive a generator, rotor, fan, etc.

At the heart of every modern gas turbine is the turbo set, consisting of a compressor and a turbine. In practice, these components are built using very different construction principles, and they can be operated independently of each other.

The demand for turbomachinery, particularly compressors, grew towards the end of the 19th century, as the industrial boom created heightened demand for compressed air. Today still, impetus for the ongoing development of compression technology comes from many different areas. In recent years, a number of new, and in some cases very specific requirements have surfaced for compressors that are to be deployed in sophisticated, environmentally sound power plants.

Up with efficiency levels, down with energy consumption

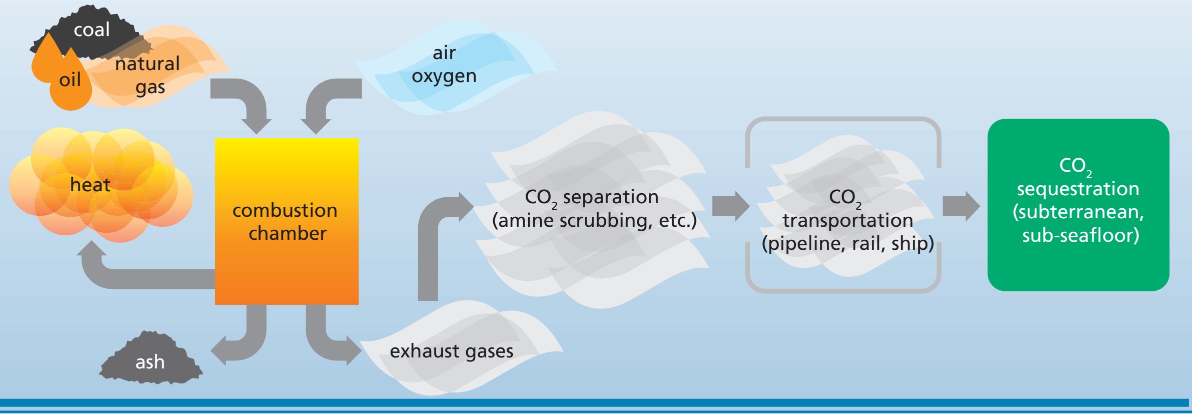
As we all know, the burning of fossil energy carriers is causing the world's temperature to rise. Next to transport and heating, one of the main culprits is the conventional generation of electricity, which is responsible for around 35 percent of fossil energy usage today (coal, gas, oil etc.). It releases tremendous quantities of the greenhouse gas carbon dioxide (CO_2) into the atmosphere. What we need are effective strategies for reducing these emissions or eliminating them altogether.

One way to alleviate the CO_2 problem is to increase the efficiency of fossil energy power plants. The current average efficiency level of existing coal-fired power plants is around 32 percent. With the help of modern technology, efficiency levels can be increased to around 50 percent by 2020. Turbomachinery will play a vital part in this. By modifying the process control – for example, by instating combined gas and steam turbine cycles that considerably rely on turbomachinery – an efficiency level of up to 60 percent can be achieved. However, this target can only be reached if the turbo components (compressors, turbines) of the deployed gas turbines are technologically very advanced. This is an area where engineering research can actively contribute towards environmental protection, as with an improved efficiency level the same power output can be achieved using less fossilenergy. On the one hand, this cuts down on the exploitation of natural resources, and on the other it reduces environmental pollution. Of course, this approach does not actually eliminate CO_2 emissions as such. Increasing attention is therefore also being paid to concepts whereby CO_2 is separated out directly in the power plant and stored safely in a climate-neutral way.

ASME, JT, Jan. 2005. Heron's Aeolipile, a steam-driven rotor (around 60 AD)

Separation and transport of carbon dioxide

The emission of greenhouse gases caused by the combustion of fossil energy is accelerating climate change. In March 2007, the EU ruled that by 2020 the total amount of emissions across Europe is to be reduced by 20 percent from 1990 levels. Concurrently, the exploitation of renewable energies across Europe is to be increased by 20 percent. With such ambitious targets, in-house separation of CO_2 from exhaust gases and its subsequent storage inside geological formations has become a key technological goal for power plants.



Flow chart of CO_2 sequestration

This strategy, also known as "sequestration", is fast becoming an important research focus internationally – particularly for emerging markets such as India, China and South Africa that produce large volumes of coal. Carbon dioxide is an unavoidable by-product when fossil energy sources are burnt, but the exact amount and composition of the exhaust gases can vary greatly depending on the energy generation methods used. When the fossil energy carrier is combusted in an atmosphere of pure oxygen, for example, the CO_2 in the exhaust gases will also be very pure (Oxy-fuel method). This technology is not without its disadvantages – the production of oxygen on an industrial scale is still very costly. Suitable methods include conventional high-pressure air separation (the Linde method) and membrane technology, in which pure oxygen is separated from the atmosphere at temperatures above 850 degrees Celsius. Power plants that wish to employ such technologies require sophisticated modified compressors for extracting and transporting large volumes of oxygen.

When fossil energy carriers are combusted in normal air, the exhaust is contaminated, and these contaminations have to be extracted before the CO_2 can be transported and stored. With the carbon capture and storage (CCS) method, the carbon dioxide is stored underground. Suitable repositories in Germany include former natural gas deposits, as well as very deep, not mineable coal seams and salt formations. Deep saline aquifers – geological strata filled with salt water at depths of 1,000–1,400 metres – are also suitable if they are completely sealed off. Unfortunately, these types of natural repositories are scarce around the world, which is why this new technology will only be applicable for a relatively short period of time. If, for example, the combined CO_2 emissions from Germany's power plants were all to be stored using the CCS method, the country's natural repositories would be filled up within 70-100 years.

There are currently two scenarios for disposing of the extracted CO_2:

1. The CO_2 is transported to the repositories via pipelines and then injected as pressurised fluid.
2. The CO_2 is compressed into a fluid state immediately after being separated in the power plant and afterwards shipped to the repositories, and pumped in.

In highly industrialised countries such as Germany, the volumes of carbon dioxide to be disposed of are vast, which is an important aspect to consider when it comes to compressing the CO_2 into fluid as this is a process that requires high pressure levels (110 bar). The entire procedure, from separating the pure CO_2 to storing it in a suitable repository, is very elaborate and can only be justified if all the stages are both efficient and environmentally sound. The production of pure oxygen, the separation of CO_2 from the exhaust gases, and the compression and transport of the CO_2 all require a lot of energy and are also very costly. It is predicted that the energy required for the CO_2 disposal cycle will be between 10 and 20 percent of a typical power plant's overall energy requirements. Pessimistic predictions go so far as to claim that the price of electricity will double. Although the power plants would be much better for the environment, in practice they would also be much less efficient.

Current discussions show that acceptance of the new technology is still very much divided. However, this will change as the costs begin to drop. Around half of the required additional energy – as well as a large part of the additional financial investment – will be required for the new compression technology. If the manufacturing of the compressor components becomes more cost-efficient, and if the operational costs reduce as a result of improved efficiency levels, there will be a lot more acceptance of CO_2 separation within the general public. In terms of technology, then, the most important task is to modify crucial aspects of the deployed turbomachinery and adapt it to the new requirements.

Multi-stage centrifugal compressors

The main focus of the process technology involved is the separation of CO_2 from the exhaust gas, and the disposal of the waste product. In the case of Oxy-fuel processing, the combustion stage needs to be preceded by large-scale, high-pressure air separation. High pressure levels are similarly required for liquefying the large volumes of extracted CO_2. The CO_2 furthermore needs to be transported away via pipelines.

All of these processes require specialised turbo compressors. Multistage, single-shaft centrifugal compressors are ideal for producing the very high overall pressure level that is needed. In such systems, however, the power used by the compressors alone can be up to 20 percent of the total plant output. As a result, the operating and investment costs required for the compression line make up a large portion of the power plant's total costs. If the compressors are built more cost-efficiently, this will contribute substantially to the plant's overall profitability. Centrifugal compressors in particular are still comparatively inefficient, oversized and expensive; there is plenty of scope for both technological and economical improvement. Of course, any reduction in manufacturing and operating costs will require increased research and development.

DLR has already been experimenting with single-stage compressors with very high stage pressure ratios. For example, a compactly designed centrifugal compressor stage has been successfully tested for aerospace use. Stage pressure ratios of around 6:1 require peripheral speeds of around 2,100 km/h at the impeller exit, which necessitates the use of materials with high mechanical load capacity. High impeller speeds also mean that the flow velocities in the compressor's flow channels will be correspondingly high. The high flow velocities cause supersonic flows around the impeller and guide vanes, which in turn will cause flow shocks, decreased efficiency, and excessive noise. CO_2 behaves differently to air, which further exacerbates the supersonic problem. The impeller and guide vanes need to be contained within a housing to shield them against the environment.

In order to achieve the required efficiency, the gap between the rotating impeller and the housing has to be very small. DLR's test compressor has a design shaft speed of 50,000 rpm, and the gap between the impeller and the housing is around 0.5 mm. Heron of Alexandria could only marvel at this; his invention was designed for entirely different operating conditions. When the new power plant technology is introduced, high-load compressors as described will not initially be a priority. However, they will propel forward the further development of high-performance stationary compressors for power plants.

With the 3D computational methods and optical measuring techniques available today, we can visualise flow processes within a compressor's supersonic flow channels that simply would have been impossible in the past. This will lead to improvements in both efficiency and construction size and will in turn decrease operating and investment costs – and ultimately contribute to reducing the environmental burden. In the short and medium term, the given environmental targets will only be achievable if the question whether turbomachinery can help the environment is answered with a resounding "yes" – and if the question mark that keeps appearing behind this topic is replaced with an unmistakeable exclamation mark.

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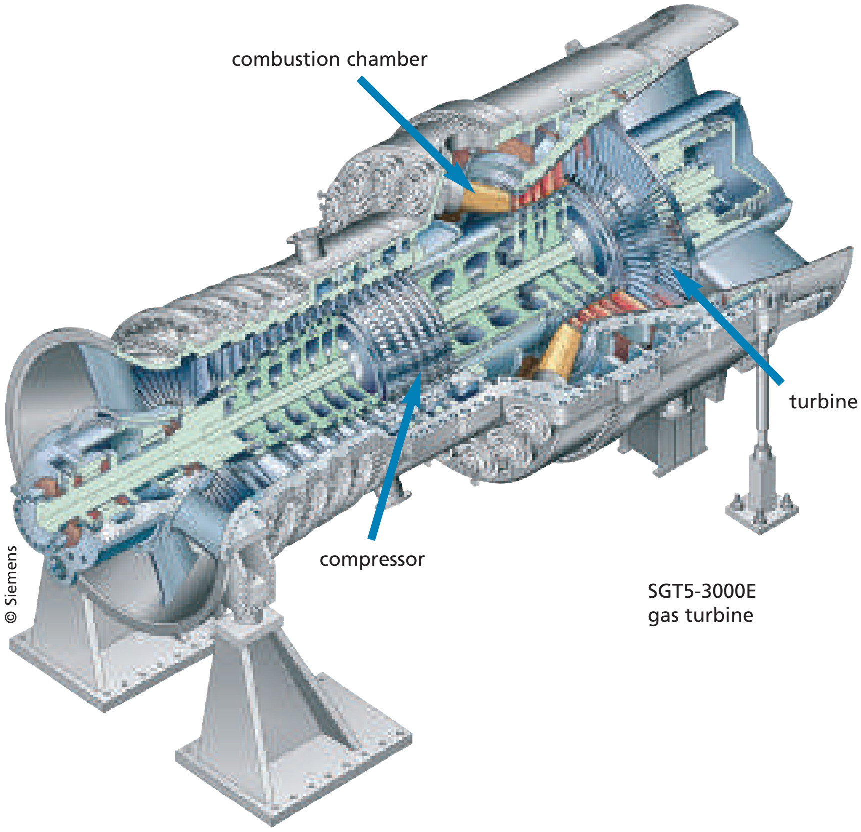

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SGT5-3000E
gas turbine