BOOSTHEAT THERMAL COMPRESSION,

INNOVATION AND POTENTIAL

BOOSTHEAT
ENERGY UNITES PEOPLE

1 / CONTEXT & PURPOSE OF THE WHITE PAPER

In the current global energy and environmental context, where demand is constantly rising and resources are running out, it is essential to develop innovative technologies with greater efficiency and less impact on the environment. These solutions must allow an increase in energy efficiency and the use of an energy saving approach.

BOOSTHEAT has developed an innovative technology of "Thermal Compression" with the aim of taking better advantage of the primary energy (not transformed), from the primary supply to the final user.

This innovation ensures the dual objective of reducing non-renewable primary energy consumption and reducing associated greenhouse gas emissions.

This thermal compression approach simply requires an external heat source. The exploitation of heat from fossil fuels; renewable fuels; solar thermal energy or any other medium temperature energy source is therefore possible.

This disruptive solution opens up vast application possibilities:

- Gas compression,
- Heating, air conditioning and domestic hot water production in the building sector,
- Industrial heating applications (processes),
- The valorization of low temperature thermal energies,
- Micro-cogeneration (mCHP) and tri-generation (mCCHP).

With its thermal compression technology, BOOSTHEAT introduces for the first time a so-called "thermal compressor". The configuration of the compressor could be likened to the one of a Stirling engine, where the working piston is replaced by two valves: one suction valve and one pressure valve.

Since 2016, BOOSTHEAT has been adapting its technology for purposes of developing a gas heat pump, integrating its first-generation CO_2 thermal compressor, to target a first application, heating and domestic hot water production in residential housing.

This white paper is intended for industrialists to help them understand the basic principles of the BOOSTHEAT innovation and its considerable advantages.

It will include:

- A reminder of the fundamental principles of thermal machines with a focus on those of the Stirling engine,
- The principles of thermal compression as seen by BOOSTHEAT,
- The research conducted by BOOSTHEAT on thermal compression and its first technical orientations,
- The potential of thermal compression technology,
- The presentation of the CO_2 thermal compressor developed to provide a gas heat pump for domestic heating,
- The field of possibilities for this technology.

2 / INTRODUCTION TO THERMAL MACHINES

- What is a thermal machine?
- The BOOSTHEAT innovation is inspired by the principle of Stirling engines, what is a Stirling engine?
- How has BOOSTHEAT taken advantage of these principles?

2.1 Fundamental principles

Thermal machines are part of energy conversion machines. They allow the conversion of heat into mechanical energy or vice versa.

If the machine converts thermal energy into mechanical energy, it is known as a driving machine, otherwise it is known as a receiving machine. In driving and receiving machines, the conversion of energy is governed by the principles of thermodynamics. According to the second principle of thermodynamics, energy conversion is only possible when there are two sources of heat, one hot and one cold.

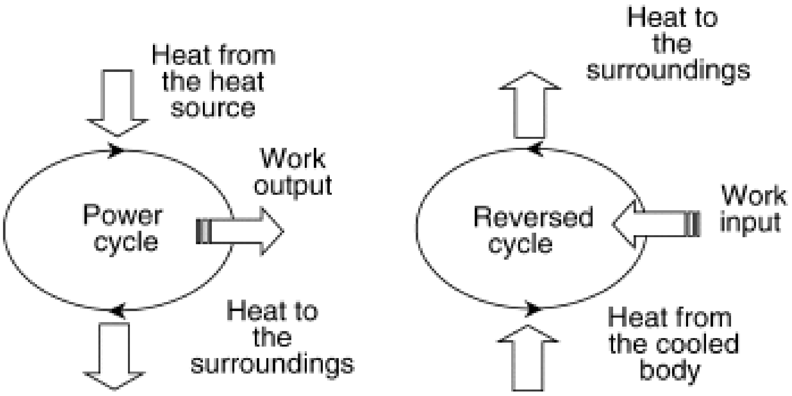

Figure 1. Thermodynamic cycles of thermal machines

In the case of a driving cycle, the working fluid receives heat from the hot source and supplies heat to the cold source. For a receiving machine, the process is the reverse of the one for a driving machine (see Figure 1). The theoretical maximum efficiency that a thermal machine can achieve is the efficiency of a perfect Carnot cycle.

To grasp the perfect Carnot cycle, the principles and basics of the Carnot machine are shared in Appendix A.

2.2 The example of Stirling engines

The Stirling engine is a thermal machine that is both a driving and a receiving machine. The driving cycle is described by a valorization of a hot source in mechanical work. The receiving cycle is described by a consumption of mechanical work for the production of cold. The Stirling engine belongs to the family of "hot air engines".

Invented by Pastor Robert Stirling in 1816 (Figure 2.1), it was very successful for several years before internal combustion engines came into existence. Despite their many advantages, Stirling engines are still in the background compared to other technologies that have been implemented since the beginning of the motorization era because of their lack of competitiveness.
The current energy context allows this technology to address the small but growing market of micro-cogeneration[1] and the valorization of waste heat[2].
Synthetically, a Stirling engine consists of five working spaces (see Figure 2.2): a compression space C and an expansion space E, a regenerator R, a cooling exchanger K (cold source) and a heating exchanger H (hot source).

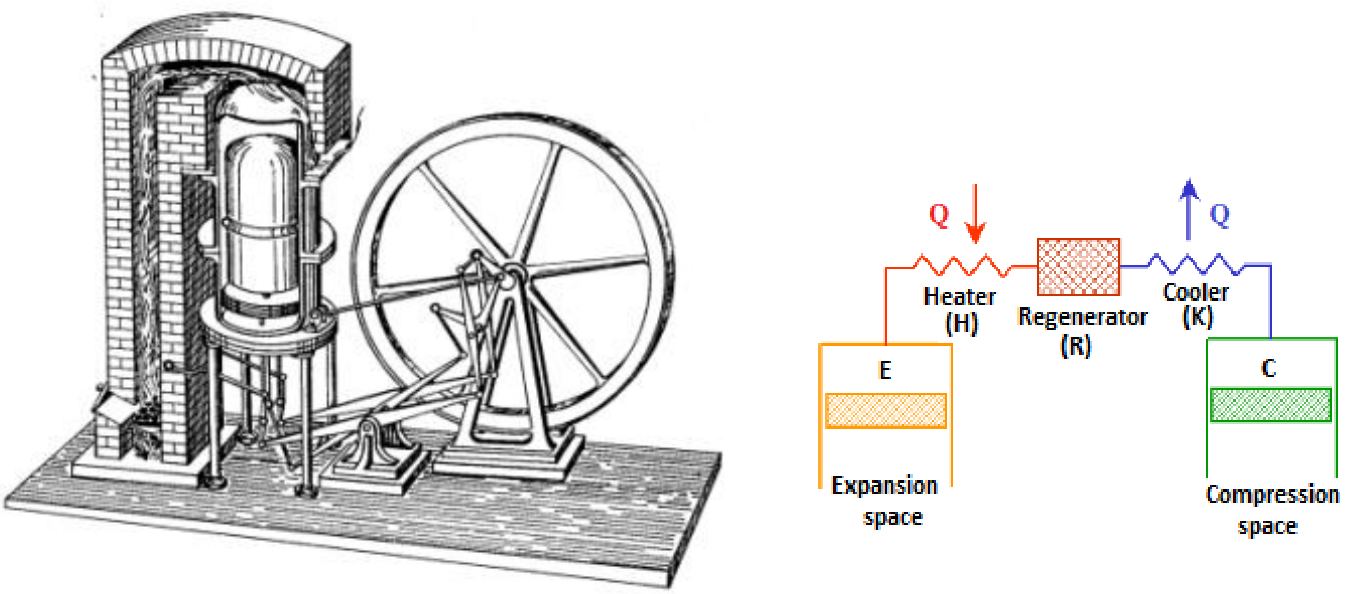

Figure 2.1. Stirling hot air engine (1816)

Figure 2.2. Schematic diagram of a Stirling engine

Figure 2. Stirling engine

The working fluid (gas) oscillates between the two compression and expansion spaces, passing through the heat exchangers to be heated or cooled.

To understand how a Stirling engine works, a representation of its thermodynamic cycle is shared in Appendix B.

2.2.1 Advantages

Stirling engines have several advantages over other engine technologies:

- Quiet running, with no explosion and no internal combustion,
- High efficiency (>30%) comparable to internal combustion engines,
- An external heat supply allowing a variety of exploitable sources: combustion of various gases, biomass, solar energy, waste heat, etc...,
- A long service life associated with easy maintenance.

2.2.2 Historical technical limits and obstacles

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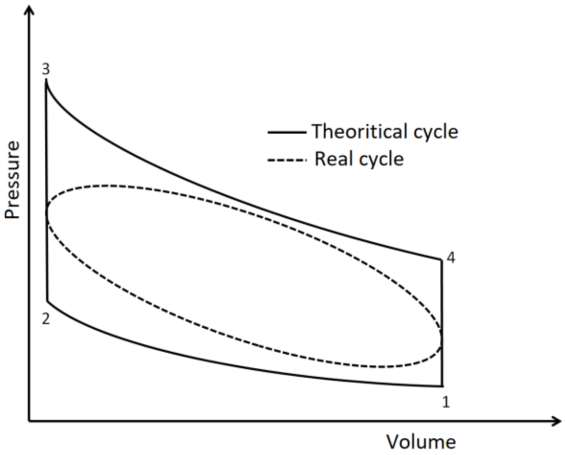
[1] Simultaneous production of heat and electricity (electric power < 36 kW).

[2] Thermal energy produced by a process, and which is neither recovered nor valorised.

Figure 3. Theoretical vs Real Stirling cycle



In a theoretical Stirling cycle approach, the amount of heat received by the gas during isochoric compression (constant volume) is the same as the one it gives up during isochoric expansion (perfect regenerator).

The heat transfers between the engine and its environment consist of a heat input at the temperature of the hot source T_C and a heat release at the temperature of the cold source (T_f).

Under these conditions, the theoretical efficiency of a Stirling cycle is similar to the maximum theoretical efficiency that a thermal machine can have (Carnot efficiency)

The real cycle described by a Stirling engine is different from the theoretical cycle presented above. The figure above shows the diagrams of the two cycles.

The main causes, which make the real cycle differ from the theoretical one, are the following:

- Imperfection of the heat exchangers,
- Imperfection of the regenerator,
- Volumes of the exchangers are equivalent to dead volumes, these spaces are therefore unswept by the pistons,
- Non-isothermal compression and expansion transformations,
- Imperfect synchronization of the pistons: the theoretical movement of the pistons is discontinuous; it presents phases of movement and phases of rest, whereas in practice, the movement is continuous.

Despite their many advantages, Stirling engines have not been as industrially successful as internal combustion engines. Since these engines rely on external combustion, it takes a certain amount of time due to the inertia of the engine to react to changes in the amount of heat applied to the hot source.
This process therefore results in:

- A motor that requires some time to warm up before it can produce useful power,
- A motor whose useful output power cannot be modified instantaneously.

At the time, Stirling systems were mainly designed for mobility needs, which very quickly presented disadvantages compared to internal combustion engines, the market privileged the reactivity to the efficiency of existing systems.

These constraints, unknown to internal combustion engines, have led Stirling engines to remain unused in large-scale production. Over the last few years, it is relevant to note the renewed interest in these machines for micro-cogeneration applications and the valorization of energy sources made possible by the contribution of external heat (biomass, solar, waste heat...) which can tolerate a certain level of inertia.

2.2.3 Efficiency

Dead volume is the total volume of working fluid which occupies the dead space in the engine. These dead spaces include the regenerator and heat exchangers. In any real Stirling cycle, this dead space is unavoidable and should be minimised wherever possible to maximise the efficiency of the engine.

The figure 4 illustrates the drop in thermal efficiency as the amount of the dead volume increases for different values of regenerator efficiencies.

The degradation of engine efficiency is observed with the increase in dead volume, but also with imperfect regeneration.

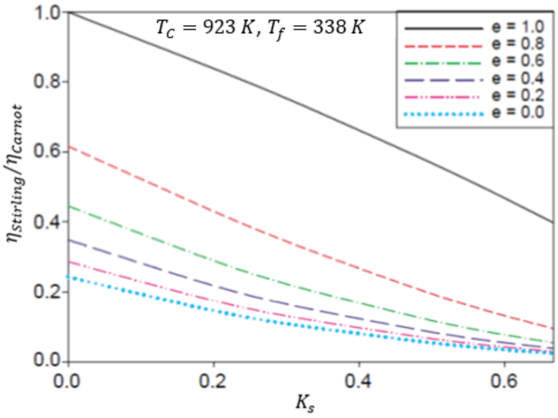


Figure 4. Effects of dead volumes and regenerator efficiency on thermal efficiency

[1] K_s: ration of dead volume

A first variation of the Stirling engine in a regenerative thermal compressor of a gas (replacement of the working piston by two valves, one for suction and the other for discharge) was first introduced in a patent of 1935 (US2, 157, 229). Another patent from 1968 (US3, 413, 815) was for the use of a regenerative thermal compressor in a refrigeration cycle as a replacement for a mechanical compressor. In both inventions, there is mention of the direct transformation of thermal energy into a gas compression energy potential without the interposition of mechanical power.

In its initial reflections, BOOSTHEAT considered the study of two patents derived from the Stirling engine but applied to the direct transformation of thermal energy into an efficient compression energy potential.

BOOSTHEAT has taken advantage of the technological evolutions of the Stirling engine (more efficient heat exchangers, reduction of mechanical losses...) and of the science of materials to solve the historical technical obstacles and to propose a new simple and efficient solution of thermal compression.

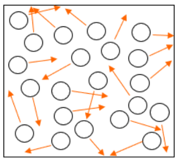
3 / BOOSTHEAT THERMAL COMPRESSION

- Understand foundations of BOOSTHEAT thermal compressor innovation?
- Why BOOSTHEAT’s thermal compression differs from others existing solutions?
- What does the BOOSTHEAT solution provide?
- What is the potential for "modeling result" compression?

3.1 Thermal compression concept

One of the applications of thermal compression is the pressure cooker.
The heat increases the pressure and thus the boiling temperature of the water, allowing food to be cooked more quickly.

The pressure of the gas on the surfaces of the chamber comes from the sum of the shocks of each molecule or atom of the gas on the surfaces.
The pressure can be increased by increasing the temperature of the gas, which has the effect of increasing the agitation and speed of the molecules.



In thermodynamics, for a perfect gas, the pressure (P) and the temperature (T) are linked by a simple equation which involves the quantity of matter (n), the volume (V) of the gas and a constant R.

$$P \times V = n \times R \times T$$

It is obvious that if the quantity of matter (n) and the volume (V) are constant, the increase in temperature leads to an increase in pressure. This is one of the ways to increase the pressure, like the volumetric compression which uses the variation of volume to increase the pressure.

To familiarize with the principles of thermal compression and to get an overview of the existing technologies, please refer to Appendix C.

3.2 The BOOSTHEAT innovation: a disruptive technology

In addition to the direct use of thermal energy from a variety of sources, the originality of BOOSTHEAT's thermal compression system lies in the absence of any mechanical compression device, work transmission, or thermochemical processes. One of the most important aspects of thermal compression is its technological simplicity.

From the mechanical point of view, the thermal compressor is made up by the following components as it is illustrated in Figure 5:

- A casing or cylinder,
- A displacer piston (D),
- A heater (H), a regenerator heat exchanger (R),
- A cooler (K),
- An inlet valve (IV) and an exhaust valve (EV).

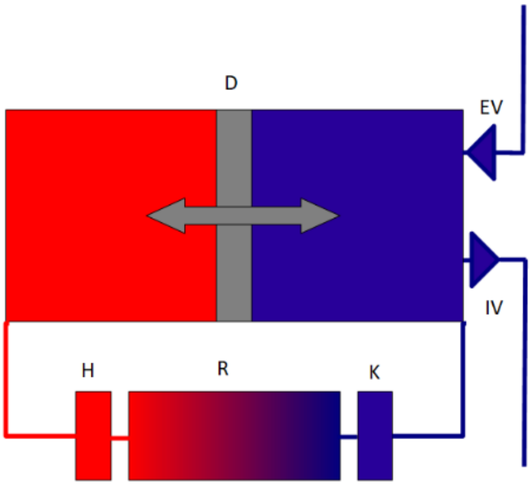


Figure 5. Representation of thermal compression solution

The main advantage of the system is that despite its great structural simplicity, it ensures all functions equivalent to a system composed of:

- A thermal engine with external heat supply,
- A power transmission,
- And a mechanical compressor.

The most important feature of the BOOSTHEAT compression approach is that the working fluid of the power cycle allowing the compression is the compressed fluid itself. The simplicity and performance of the heat driven compressor result from this essential feature. This feature allows the absence of any mechanical compression and power transmission device.

From a technological point of view, the solution has a certain number of characteristics in common with external heat regenerative engines such as Stirling or Ericsson engines. Among other features, it has functionally equivalent heat exchangers (including a regenerator).

3.2.1 Dynamic description

The heat driven compressor performs a mechanical work of compression on a fluid without mechanical compression piston. The displacer role is similar to that of the displacer (as opposed to power piston) of a Gamma type Stirling engine, which is to ensure the movement of some fluid between the hot and cold parts of the cylinder through the exchangers (H-R-K). At any time, the communication between the hot and cold parts of the system is open.

The **pressure remains uniform in the whole device** (except for pressure losses), and **the piston does not transmit mechanical power** to compress the fluid. The absence of mechanical compression device and the mechanical simplicity of the compressor will also provide an excellent mechanical efficiency compared to a system made up of engine/power transmission/ compressor, particularly at the level of the piston rings/cylinder friction.

3.2.2 Thermodynamic cycle

The thermodynamic cycle described by one stage of the thermal compressor is made up of four processes (Figure 6):

- An **isochoric compression (1-2)** due to heat transfer. The valves are closed. The displacer is initially on the left dead centre and moves towards the right. Therefore, the working fluid at initial pressure P1 is transferred from the cold part to the hot part of the cylinder through the three heat exchangers K, R and H. The total volume of the system is constant. The fluid pressure gradually increases up to pressure P2.
- An **isobaric exhaust (2-3)**. At pressure P2 the outlet valve opens and a mass of fluid is pushed out of the cylinder as long as the displacer moves towards its right hand side dead center.
- An **isochoric expansion** (3-4) by cooling. Both valves are closed. The displacer moves towards the left so that the working fluid flows from the hot side of the cylinder to the cold side of the cylinder. The total volume of the system is constant. The working fluid pressure gradually decreases from pressure P2 down to pressure P1.
- An **isobaric suction**. At pressure P1 the inlet valve opens. A mass of fluid is sucked into the cylinder as long as the displacer moves towards its left hand side dead center.

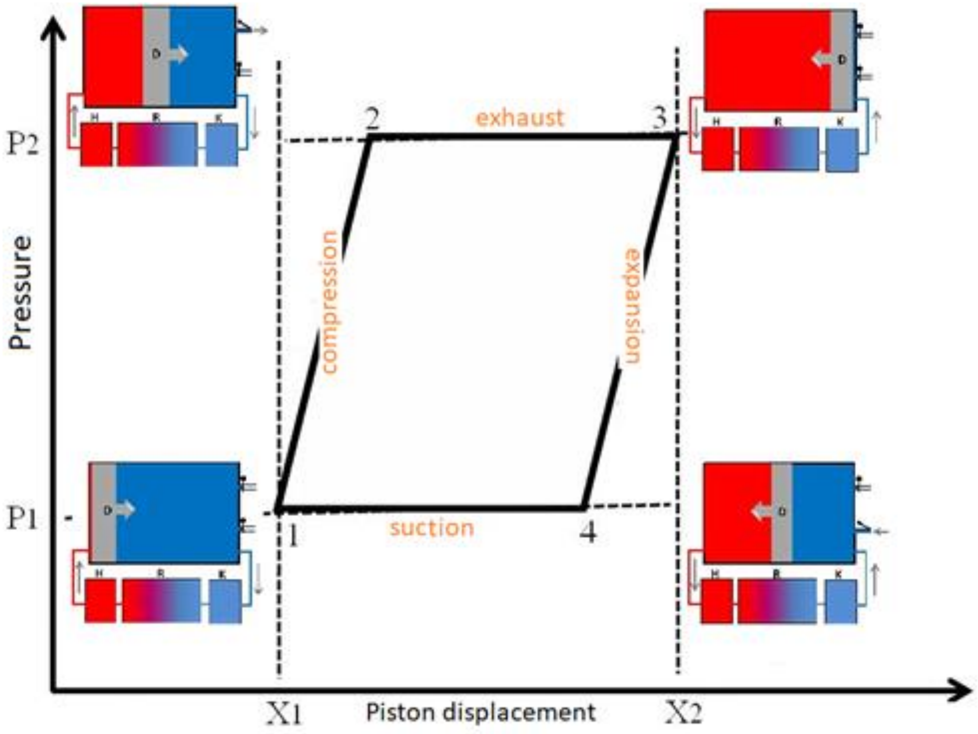


Figure 6. Thermodynamic cycle of BOOSTHEAT thermal compression

Take Away

This new simple and original thermal compression concept offers a multitude of evolutions allowing to answer efficiently the needs of any type of application requiring a gas compression process. The fields of evolution of the Boostheat thermal compression concept remain wide and diverse.

3.3 Potential of thermal compression

Using the thermal compression developed by BOOSTHEAT, it is completely possible to obtain higher pressure ratios than those achieved in the current design (of the order of 3 for one stage versus 1.6 currently) while maintaining the basic concepts of geometric hypothesis.

It is worth noticing that the physical dimensions related to the operating conditions of the fluid (P/T in particular) and the type of external heat used will lead to choosing to restrict the achievable pressure rates to reduce the mechanical constraints that the future product will undergo.

For applications requiring higher pressure ratios, it is therefore appropriate to make several compression stages in series.

A two-stage compression solution in series could be implemented with a double-acting compression architecture (compression in two chambers in the same cylinder). This architecture will meet the needs of applications requiring higher pressure ratios with increased technological simplicity.

3.4 "Research to Development" retrospective from 2011 to 2019

From 2011 to 2019, BOOSTHEAT focused its research activities on providing innovative answers to the technical challenges related to the development of its technology for industry. In parallel to these activities, the company kept on patenting its concepts to remain a forerunner in efficient thermal compression solutions.

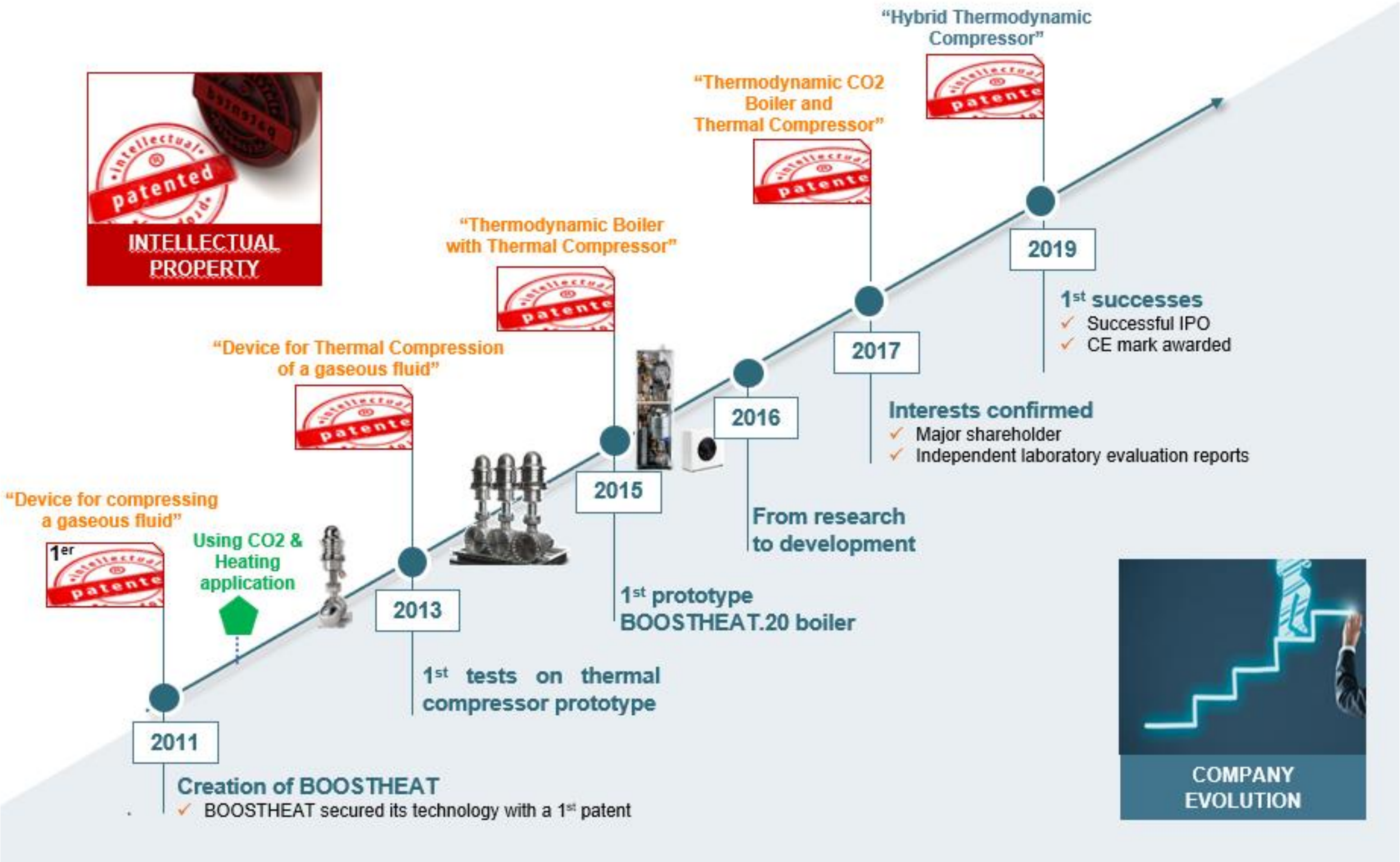


Figure 7. Evolution of BOOSTHEAT Patents and Company

The research work went through three major phases: from the fundamental research phase, through exploratory research to applied research. The purpose of this research was to support the development of its first thermal compressor for a first targeted application: the production of efficient heating in residential housing.

4 / TECHNOLOGY AT THE SERVICE OF INDUSTRY: PRODUCT DEVELOPMENT FOR THE "RESIDENTIAL HEATING" APPLICATION

- Which first application did BOOSTHEAT identify to bring in its innovation?
- What was the ecosystem and competitive environment in which the product was developed?
- How did this decision lead to the technical choices made in the development of the first thermal compressor?

Aware of the ecological stakes and the interest of European politics in new technologies able to significantly contribute to the reduction of greenhouse gases in the home, BOOSTHEAT quickly moved towards a first application: the development of a thermal compressor suitable for developing a gas heat pump. With the goal of achieving a more efficient use of the primary energy from the source to the end user, this new value proposition provides an alternative to the use of electric compressors in heat pumps (HP) for home heating and domestic hot water (DHW) production as a first application.

The direct use of primary energy, by avoiding the electricity generation and transmission chains, allows to:

- Reduce energy consumption by reducing primary energy transformation cycles in power plants as well as losses related to electricity distribution. This also reduces greenhouse gas emissions,

- Cost less to the user: the more energy is transformed, the more the overall efficiency drops and the more expensive the energy is,

- Making the most of primary energy with a fair consumption that meets the needs by effectively controlling combustion and by making the most of the waste heat resulting from it,

- Valorize a renewable energy source through the PAC effect (aerothermal, geothermal, waste heat).

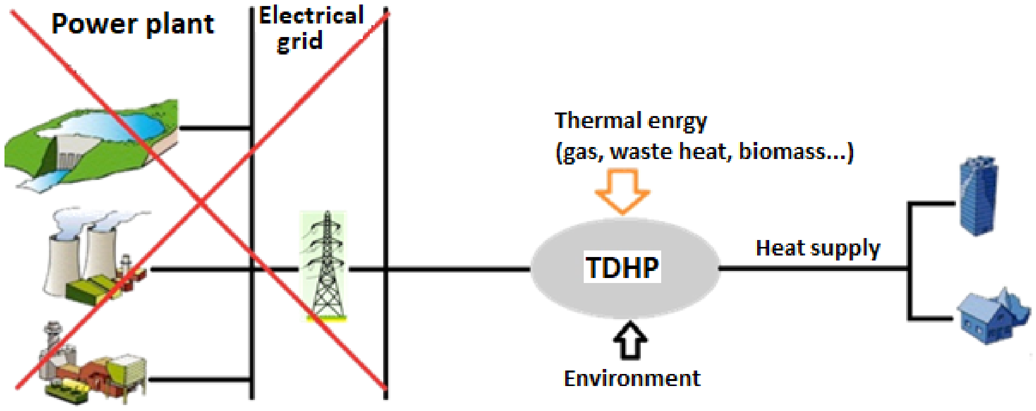


Figure 8. Elimination of generation & transmission of electricity

4.1 TDHP: competitive environment & expected KPI[3]

In order to understand the competitive environment in which BOOSTHEAT has entered by addressing the residential market, it is worth pointing out the main families of innovative "thermal" heat pump solutions.

Thermally driven heat pump means a heat pump using heat or an engine to drive the sorption or compression cycle”. There are three main type of thermally driven heat pumps recognized today; gas sorption heat pump (GAHP) and thermal compression heat pump (TCHP: where only BOOSTHEAT is present) are both covered by EN 12309 and gas engine heat pump (GEHP) is covered by EN 16905.

4.1.1 Absorption Heat pump

The gas absorption heat pump incorporates in addition to the evaporator, condenser and expansion elements (typical components of a compression system), a thermal compression system (generator, absorber and solution pump) that replaces the mechanical compressor of a traditional compression system. The device is driven by heat, which can come from various energy vectors such as natural gas, bio-methane, hydrogen or waste heat.

Robur 18kW, example aerothermal gas absorption heat pump

Absorption technology is mature and reliable. It has been used in refrigeration applications for decades. Its application to heating is merely a refrigeration cycle where the useful effect is the heat released by condenser and absorber instead of the cooling effect obtained at the evaporator.

Gas Absorption Heat Pump technology is the most widespread and mature technology within TDHP on the market, introduced over 20 years ago and currently available in different sizes and with different types of renewable energy supply (aerothermal, geothermal and hydrothermal).

Cooll adsorption prototype

4.1.2 Adsorption Heat pump

Adsorption heat pumps can, for example, use water or ammonia as a refrigerant. Transfer of ambient energy to the system is achieved by evaporating the refrigerant. The refrigerant (water or ammonia) vapor is adsorbed at the surface of a solid (e.g., zeolite or activated carbon). This process releases heat at a higher temperature level. Once the adsorbent is saturated, the refrigerant is expelled in a desorption phase using heat from a fuel burner. Whereas absorption functions continuously, adsorption technology is a cyclic process (adsorption/desorption), which appears to be continuous due to the response time of the heating circuit and respective heat pump design (e.g. more than one adsorption module phase shifted) and control

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[3] This chapter is an extract of information from EHPA “Thermally driven heat pumps - how they work and why they matter”

4.1.3 Gas engine Heat pump

Panasonic GES

Gas Endothermic Heat Pumps are direct expansion systems with a compressor of a similar type to those in an Electric Heat Pump system. A variable speed (rpm) gas engine is used as the driving source of a compressor instead of an electric motor. This gas engine compressor drive has 2 advantages: 1. Availability of waste heat from the gas engine that can be valorised. 2. No need of electrical consumption for motor power thanks to the gas engine. The main components in a GEHP are an endothermic gas-fired engine (GE), one or more rotary or scroll compressors for a vapor compression heat pump (HP), a condenser, an expansion valve and an evaporator.

In term of main key performance factors, TDHP indicators are:

- Contribution to EU energy and climate targets: CO_2-emissions reduction of 30 to 40% compared with traditional heating technologies), primary energy savings and efficient use of energy, diversification of energy sources. When using renewable gases in TDHP, CO_2 emissions can be further reduced,
- Reduction in primary energy required compared to traditional heating technologies of up to 40%,
- Good performance at low outdoor air temperatures (not only on ground source applications) and higher heating supply temperatures (also with radiators),
- Feed-in temperature up to 70°C: compatible with “retrofit applications” and DHW requirements.
- Reversible heating & cooling possible,
- The ability to provide high output temperatures allows TDHPs to be directly used with existing heating systems. “High temperature levels” means heating and DHW supply temperatures 55°C and higher.

4.2 Development of the first BOOSTHEAT CO_2 thermal compressor

The development of the BOOSTHEAT thermal compressor had to meet the need for a thermal heat pump solution (e.g. gas-driven) compatible with the domestic heating market.

This strategic orientation therefore determined the technical characteristics of the first BOOSTHEAT compressor:

1- To be able to produce a heat generator compatible with the standards and constraints imposed for domestic boilers for powers from 8kW,
2- To be able to operate with a refrigerant compatible with the F-GAZ directive and anticipate its evolutions which are becoming more and more restrictive in terms of GWP (Global Warming Potential) limits,
3- To reach a level of performance that differentiates it from existing thermal systems while guaranteeing a relevant return on investment to break into the residential housing market.

4.2.1 Selection of the working fluid

The term refrigerant refers to a fluid that allows the cycle used in a thermodynamic machine such as a heat pump or a refrigeration unit (your refrigerator or the air conditioning of your car, for the smaller systems).

The choice of such a fluid in a thermodynamic machine must take into account its physical properties (such as its density) but also environmental and safety constraints.

CO_2, considered as a natural fluid, having an impact on the greenhouse effect in the weakest among all the refrigerants, non-flammable, non-toxic, widely available and very stable when it is submitted to an increase of temperature (no degradation of the molecule), is thus perfectly adapted to the thermal compression used in a thermodynamic machine. Thus, BOOSTHEAT's initial decision to use CO_2 for the development of its machine was the most relevant considering the properties of CO_2 and comparing it with existing refrigerant solutions in 2012-2013.

Section 5.2 discusses the compatibility of other fluids with BOOSTHEAT technology. An internal study was conducted to summarize the compatible fluids. It is a comprehensive study that considers all technical, thermodynamic, environmental and safety criteria that a refrigerant must meet.

4.2.2 Integration in a CO_2 heat pump cycle

The thermal compressor invented by BOOSTHEAT is designed to be incorporated into a thermodynamic cycle as used in a heat pump.

The main purpose is to use the heat released by the combustion of a gaseous fuel to increase the pressure of the refrigerant and to recover the heat contained in the exhaust fumes. In this way, our system is more efficient than a condensing boiler which has no thermodynamic effect.

The refrigerant chosen for our system is CO_2 because:

- It is considered as a natural fluid,
- It has an impact on the greenhouse effect in the lowest among all refrigerants,
- It is non-flammable and non-toxic,
- It is easily available,
- It is very stable when subjected to a temperature rise (no degradation of the molecule),
- The temperature range used in a domestic heating system means that CO_2 will operate in a transcritical cycle. The fluids in the supercritical state have several advantages compared to the liquid state, in particular a high diffusivity coefficient and a low viscosity, enabling good heat transfer.

The triple point of CO_2 is at -56.6°C below 0.51 MPa and the critical point is at 31.1°C beyond 7.38 MPa. This feature is favorable for the transport of CO2 in a liquid state which is approximately around 10 MPa at room temperature.

Take Away

The current sizing of the thermal compressor corresponds to the use of CO2 as the working fluid. It is the result of an optimization of the heat exchangers for better heat transfers and fluid flows allowing to reduce the pressure drops.

An energetic representation of the thermal compressor illustrating the heat flows involved makes its quantification possible and enables the definition of energy performance parameters.

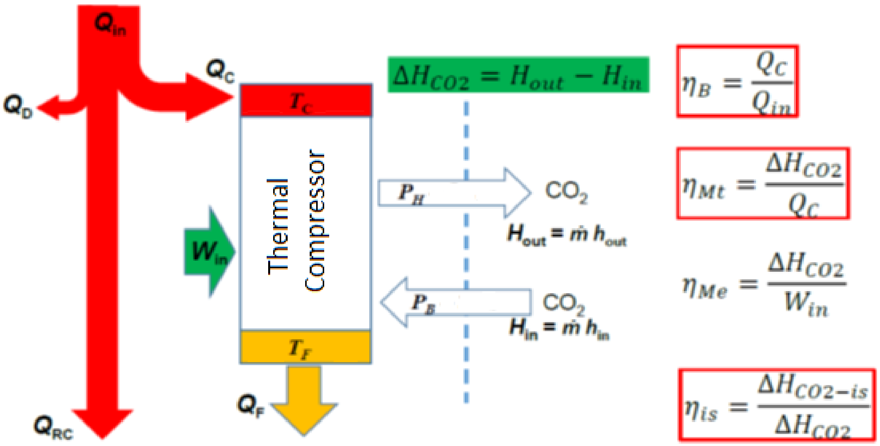
4.2.3 Energy representation of the BOOSTHEAT compressor

A schematic representation of the energy flows in the thermal compressor is proposed in Figure 9.

Like any thermal machine, the compressor draws heat from a "hot source" and rejects heat to a "cold source" in order to generate mechanical work. In the case of the BOOSTHEAT compressor, the mechanical work generated consists of sucking in and discharging the CO_2 by increasing its pressure. To a first approximation, this mechanical work can be quantified through the variation of the enthalpy level between suction and discharge.

In its first application, the heat source is the combustion of natural gas in a burner. A non-negligible part of the calorific value of the gas (Q_{in}) remains unabsorbed by the thermal compressor partly due to the high working temperatures (T_C) demanded from the hot source of the compressor (Q_{RC}) recovered in a heat exchanger, to the net of the thermal losses (Q_D). Heat rejected from the engine "cold source" could also be recovered in an exchanger for further system optimization.

Finally, the operation of the BOOSTHEAT thermal compressor also requires a certain amount of electrical power to drive the displacement piston which is negligible compared to the supply of heat (Q_C).



Q_C: Heat from a "hot source"
Q_F: Heat rejected to a "cold source".
P_B, P_H: CO_2 Suction pressure, Discharge pressure
ΔH_{CO2}: Enthalpy variation between suction and discharge
Q_{in}: Calorific power of the gas
T_C: High working temperatures
Q_{RC}: Energy recovered in a heat exchanger
Win: Electrical power of the displacer piston
η_B: Efficiency of the heater (hot part) to absorb heat
η_{Mt}: Thermal efficiency of the motor
η_{Me}: Electrical efficiency of the motor
η_{is}: Isentropic efficiency

Figure 9. Schematic representation of the energy flows in the compressor

A modeling approach of the compressor gives an appreciation of the key phenomena involved in the compressor, in particular certain energy efficiencies, to characterize it for a given application:

- The heat transfer between the burner and the engine, which characterizes the efficiency of the heater to absorb the heat from the combustion,
- The thermal efficiency of the engine, defined by the ratio of the compression work of a given mass of CO_2 to the energy absorbed by the heater,
- The isentropic efficiency.

Take Away

The energetic characterization presented above has contributed to the current design of the thermal compressor. It is based on numerical models that describe the behavior of the compressor and has led to the optimization of heat transfer in the exchangers and the minimization of pressure drops due to the fluid flow.

4.2.4 Design of the BOOSTHEAT thermal compressor

Based on the initial design calculations and research work carried out by BOOSTHEAT, it took several years to develop the first industrial version of the BOOSTHEAT CO_2 thermal compressor.

The figure below shows a cross-section view of the thermal compressor showing all the major parts of the system. Each part has been designed to ensure a specific function for the proper functioning of the compressor.

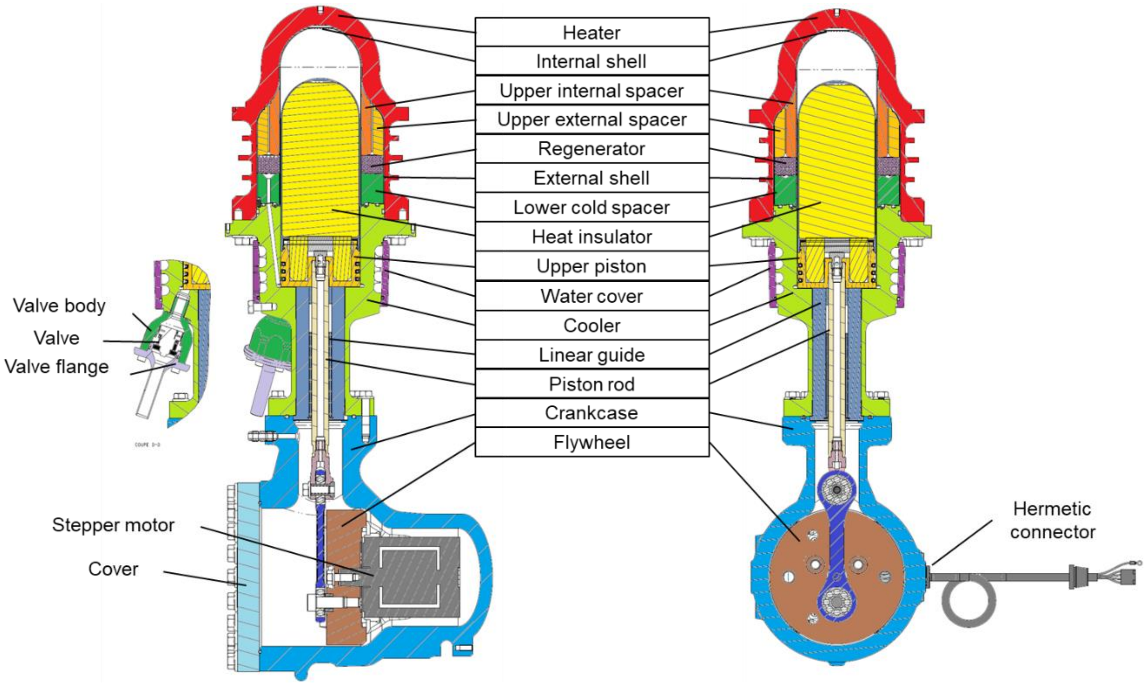


Figure 10. Cross-sectional views of the thermal compressor

4.2.4.1 Shell parts and piston kinematics

The compressor was designed as a semi-hermetic compressor (non-welded outer shell) for industrialization purposes. The design of the shell parts allows the compressor to withstand a pressure of 110 bar and to reach 800°C in the heating zone in operation, making it functional for the compression of CO_2 in its transcritical state (above 73.6 bar).

The rotation frequency is typically between 60 and 270 rpm. The kinematics is designed to preserve the rotational movement by minimizing the friction forces, especially the upper piston/internal shell and the lower piston/cooler. The accuracy of the guiding mechanism and the inertial mass allow these objectives to be met.

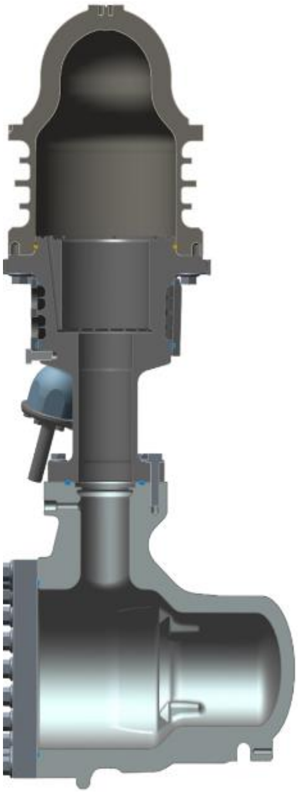


Figure 11. Shell parts and piston kinematics

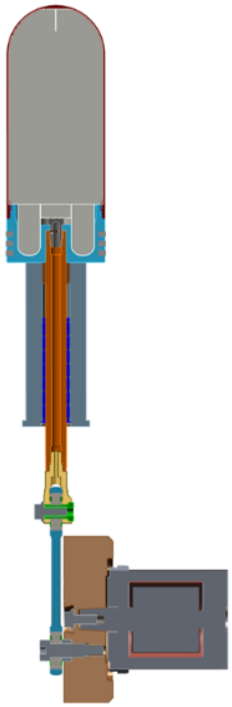
The Heater is the heat exchanger on the hot side. The part is made of stainless steel, which was chosen for its mechanical properties at the high temperature (>500°C) required for compression. The upper section is very thick and in direct contact with the flame and has a temperature sensor to regulate the heating power. The thin lower section is designed to limit the heat conduction to the cold source.

The Cooler is the heat exchanger on the cold side. The part has been designed to provide energy through an external water circulation. Made of an aluminum alloy, it prevents erosion and increases its resistance to corrosion. It may be noticed that the fluid passage channels as well as the friction zone of the segments are as close as possible to the cold source to improve the heat transfers and limit overheating.

The suction and discharge valves are also part of the compressor shell. They are designed to be removable for replacement. The valves are designed with a low pressure drop and a low opening pressure of approximately 50 mbar.

The crankcase encloses the lower part of the kinematics and the motor. It is made of aluminum for its reduced weight and ease of casting. It features an outlet for the motor power and control cable.

The **Displacement piston** is divided into two parts. The upper piston is relatively long, thin-walled and filled with a thermal insulator to limit heat exchange between its two sides. Furthermore, a relative sealing between a sleeve and the rod provides a relatively tight connection between the lower part of the cooler and the crankcase volume during operation.



The inner volume of the piston is connected with the crankcase volume through the rod at the bottom of the piston, which ensures that there is no crushing of the piston under high pressure.

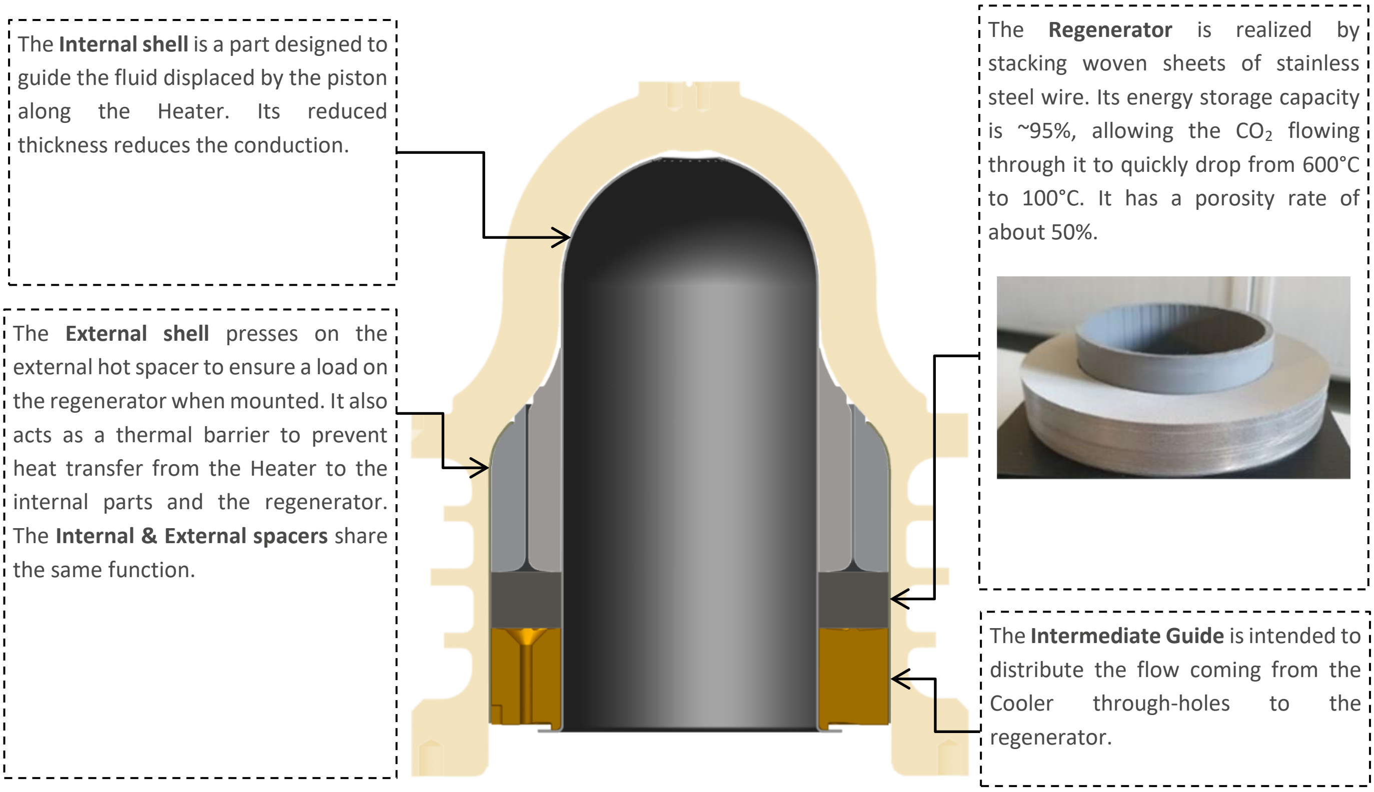
The lower part of the piston houses the Segmentation. Three specific rings are used to adapt to thermal expansion while limiting friction forces. It is a solution compatible without any lubrication and adapted to the conditions of use (<100°C). The constant cooling of the Cooler limits the temperature rise.

The linear guidance is realized with a linear ball bearing guide which offers a high precision over the whole guide length.

The driving mechanism of the kinematics is realized with a stepper motor which offers a reduced space requirement. Its remanent torque under load is relatively low, which results in a low electrical power consumption during the operation of the thermal compressor. The motor control is adapted to the braking phases by means of power dissipation in the receiver mode of the motor.

4.2.4.2 Internal fluid guidance

The fluid sucked in at each revolution of the motor is transferred to one side or the other of the piston. The upper parts of the compressor act as a fluid guide and also as a thermal barrier, which minimizes the impact of the hot source on the cold source over the long term.



The **Internal shell** is a part designed to guide the fluid displaced by the piston along the Heater. Its reduced thickness reduces the conduction.

The **External shell** presses on the external hot spacer to ensure a load on the regenerator when mounted. It also acts as a thermal barrier to prevent heat transfer from the Heater to the internal parts and the regenerator. The **Internal & External spacers** share the same function.

The **Regenerator** is realized by stacking woven sheets of stainless steel wire. Its energy storage capacity is ~95%, allowing the CO_2 flowing through it to quickly drop from 600°C to 100°C. It has a porosity rate of about 50%.

The **Intermediate Guide** is intended to distribute the flow coming from the Cooler through-holes to the regenerator.

Figure 12. Internal guides of the compressed fluid

4.3 From "thermal compressor" to "thermal compression system" in a gas heat pump

In partnership with GRDF, the company has quickly focused on the development of a first heat pump for the residential market. The global concept of the product proposed by BOOSTHEAT consists in the direct coupling of two specific thermodynamic systems (a "thermal compressor" and a "reverse cycle with vapor compression") to obtain a *Thermally Driven Heat Pump (TDHP)*.

Technologically speaking, the BOOSTHEAT compressor replaces the electric compressor of an electric heat pump, as all the elements of the heat pump circuit (evaporator/condenser or gas cooler...) remain unchanged. A heating generator with a BOOSTHEAT compressor can thus be installed as a replacement for domestic boilers, with the addition of an external standard heat exchanger (evaporator) taking free calories from the environment.

To achieve optimal compression, the system is built with three compression stages in series. The third compression stage uses the flue exhaust from the other two stages, minimizing the flue exhaust losses and maximizing the thermodynamic effect.

The diagram below shows the current configuration of the BOOSTHEAT heat pump.

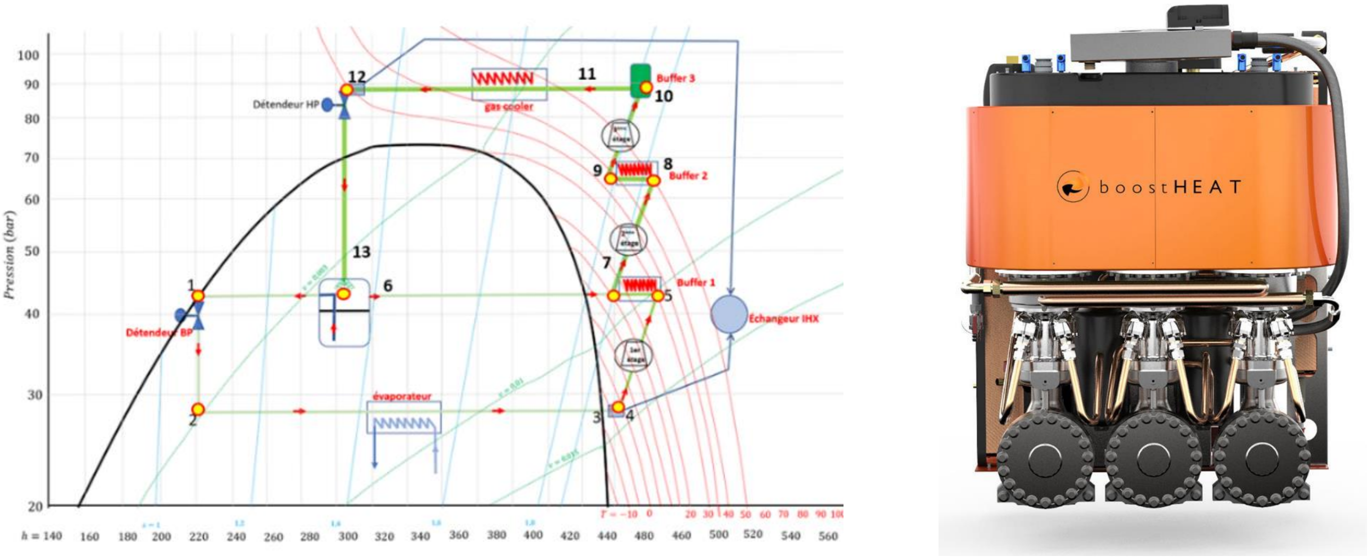


Figure 13. Current configuration of the BOOSTHEAT heat pump

Since end of 2019, BOOSTHEAT has rolled out over a hundred of TDHP in Europe, especially in the existing residential market. After one year dedicated in fine tuning the product reliability, BOOSTHEAT has increased its requirement in terms of normative performance objective to reach industry standard which has evolved to higher excellence criteria since 2015. Then BOOSTHEAT has decided to focus most of its internal efforts on its innovation, the thermal compression, and to simultaneously expand the target application range of its thermal heat pump. So, the company went through the performance improvement of heat pumps for an enlarged range of applications such as heating a single-family house and the supply of domestic hot water (DHW) for multi-family houses and collective buildings.

4.4 Changes during the development of the compressor

To strengthen the product development, BOOSTHEAT has developed various analytical tools to capitalize and accelerate the understanding of the phenomena observed during these laboratory tests and/or during the supervision of these samples in real life environments to gather the feedback.

Among these tools, the company currently benefits from:

1) A characterization of the compressor's performance: These data are derived from various single unit test campaigns carried out on in-house test benches that allow for the simulation of the compressor's operation under different conditions as well as by modeling. The approach consists in determining the optimal operating points corresponding to a given heating temperature and engine speed, which give the best performance of the compressor in terms of low thermal energy consumption, pressure ratio and highest generated fluid flow.
2) Modeling and characterization of the heat exchangers in order to observe their performance (e.g., correlations on heat transfer coefficients and friction factors or "CFD" numerical methods).
3) A numerical modeling of the compressor to analyze its thermodynamic cycle and its energy efficiency.

More information about model description and results are presented in annex D.

These different tools have led to experimentally validate evolutions, previously calculated or numerically simulated, as well as to quickly highlight the key optimizations of the compressor design.

Among these improvements, the following directions have been pursued during the development of the compressor:

- **Control of functional clearances and elimination of dead volumes:** the reduction of dead volumes has allowed to drastically increase the performance of the compressor. Adapted fitments have allowed to limit internal friction and therefore the engine consumption,
- **Regenerator sizing**: optimizing the technology and geometry to be able to store enough energy while minimizing pressure drops to reduce the motor's power compensation,
- **Fluid flows and heat exchanges**: optimization of fluid flows and heat exchanges by adapting the geometry and materials of the parts, through numerical simulations and experimental tests,
- **Improvement of the piston/cylinder sealing**: this sealing is extremely important because it avoids the bypass of the regenerator in the path taken by the fluid. However, a compromise had to be found to avoid generating too much friction.

The tests carried out on the compressor allowed the measurement of performance gains for the improvement of internal geometries (by improving pressure drops) or segmentation (by improving electric motor consumption). Figure 14 illustrates the gains in compression ratio obtained with an improvement in heat distribution on the heater.

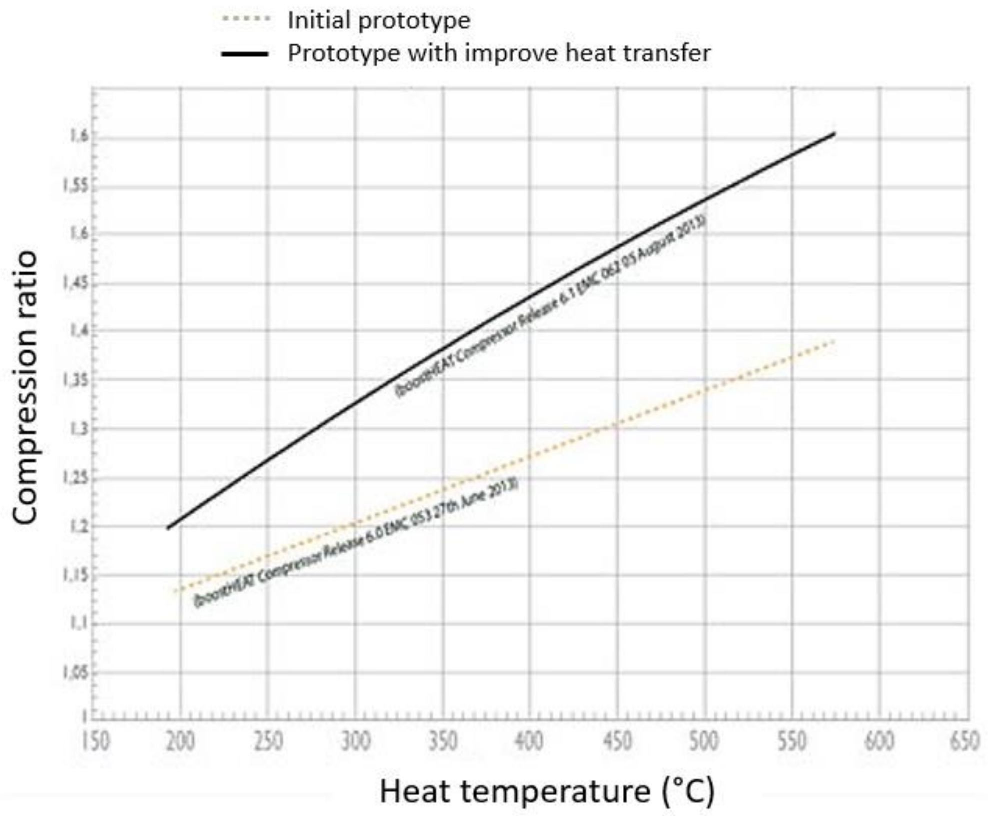


Figure 14. Improvement of the compression ratio by improving the heat distribution.

4.5 New perspectives from 2019 to 2022, "hybridization"

BOOSTHEAT expanded its research focus from 2017 to provide adaptive and efficient solutions based on thermal compression. In 2019, BOOSTHEAT submitted a patent on hybridization that enhances the ability to scale up and address new applications with a broader scope.

To understand the basic concept of hybridization proposed by BOOSTHEAT, refer to chapter 5 which illustrates the ingenious coupling between the thermal compressor and a volumetric compressor.

5 / BOOSTHEAT HYBRID COMPRESSOR

- Are there solutions to overcome the disadvantages of thermal compression (e.g. compression factor)?
- Can BOOSTHEAT technology be coupled with existing compressors to open up new applications?

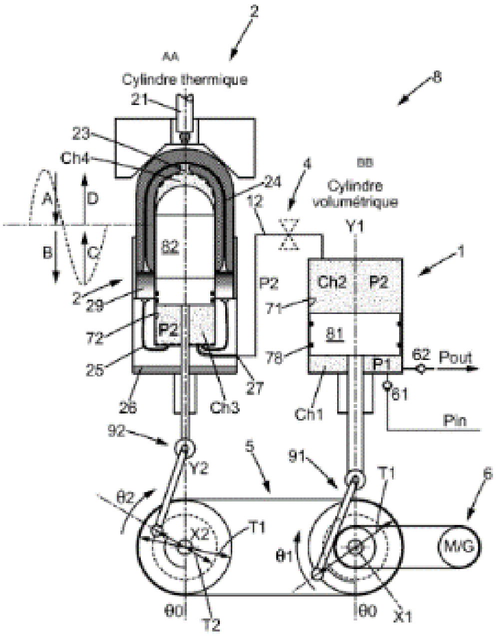


Figure15. BOOSTHEAT patent hybrid compressor

As part of its ongoing research on the thermal compressor, BOOSTHEAT has developed a new and original hybrid compressor architecture (patent registered by BOOSTHEAT in 2019). It consists of the direct coupling of a BOOSTHEAT regenerative thermal compressor and a volumetric compressor (single or double acting). In the context of a heat pump application, this innovative approach is a concrete solution in favor of the energy mix by offering a flexible system that can work with two energy sources that are subject to constraints (economically or in terms of availability) to ensure better comfort, reduced consumption, and lower CO_2 emissions.

The versatility of the solution lies in adapting to the operating conditions of the heat pump and the different energy sources available. It is possible to generate electrical energy from a thermal source as an auxiliary at certain operating times and to use electrical energy without thermal energy at other times.

The ingenious combination of these two compressors brings a new approach to the hybrid heat pump and offers many advantages for heat, cooling and power generation applications :

- Simple to implement as it relies on a mature technology (volumetric compressor),

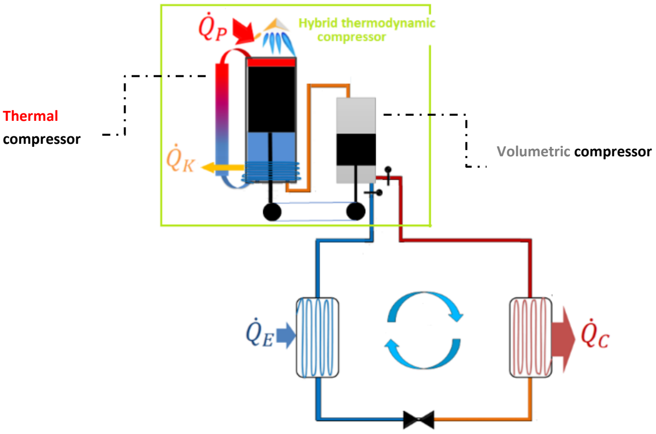


Figure 16. BOOSTHEAT hybrid compressor in a heat pump

- The system can reach higher pressure ratios thanks to the add-on compression of the volumetric compressor,
- High performance levels can be achieved,
- Good operation even when dealing with the most critical conditions of the standards (high pressure ratio, low flow rate...),
- Possibility of running solely with the electric compressor in certain conditions that are not suitable for the thermal compressor (e.g., very low power, instantaneous production demands, DHW production in summer, etc.),
- The same working fluid is used in the thermal compressor and in the positive displacement compressor. Consequently, even if there are some leakages on the segmentation area, there is no fluid mixing. In addition, the sealing constraints between the piston and cylinder are much less critical than when using two separate fluids,
- A very efficient reversible heat pump cycle,
- A micro-cogeneration compatible solution.

The implementation solution of the thermal compressor coupled with the volumetric compressor has been the subject of a patent filed in 2019 by BOOSTHEAT: PCT/FR2020/050464 HYBRID THERMODYNAMIC COMPRESSOR. This patent covers both the coupling of two compressors (thermal and volumetric) and the micro-cogeneration service that can be activated by means of a generator.

Take Away

Based on its recently filed patent, Boostheat has launched the development of a POC to demonstrate the technical feasibility of this hybrid compressor.

6 / THE POTENTIAL OF THE TECHNOLOGY ACCORDING TO THE NEEDS OR REQUIREMENTS OF THE ENVIRONMENT

- What industrial applications can benefit from the advantages of thermal compression?
- What degree of research is required to confirm the technical feasibility of the technology to meet each of these new applications?

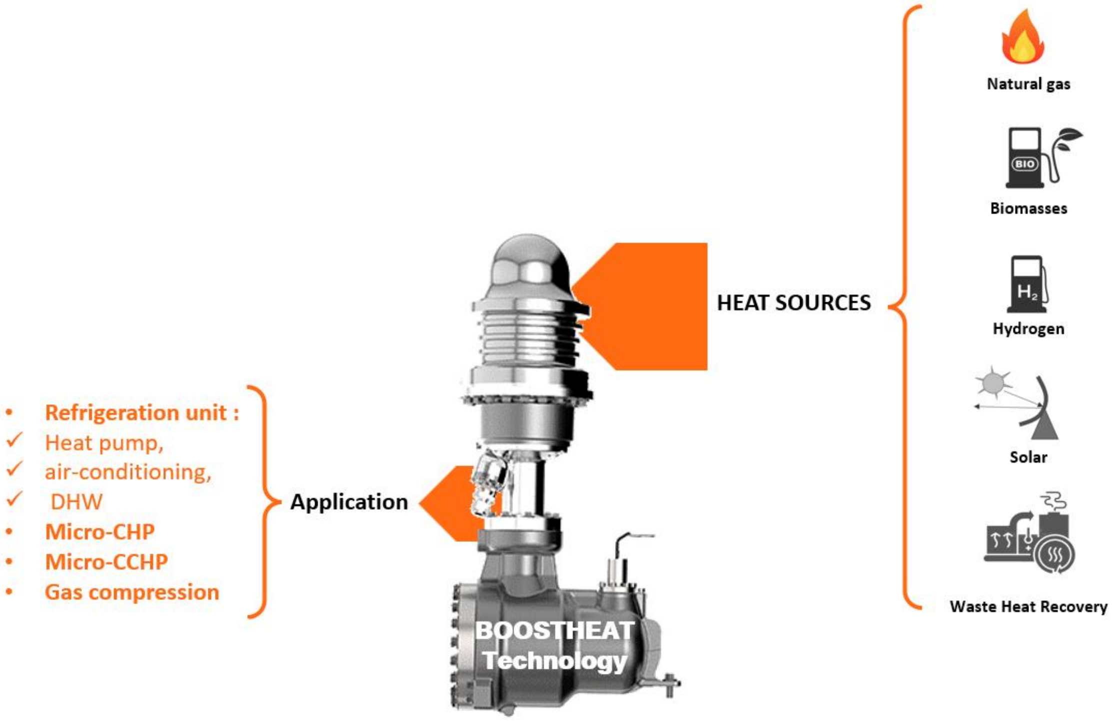
Over the past 10 years, BOOSTHEAT's strategic orientation has led the R&D program to focus its resources on :

- Fundamental research about thermal compression,
- Development of a thermal compressor prototype to provide a proof of concept,
- The industrialization and reliability of a CO_2 compressor as part of the development of its gas heat pump.

The company relies on its rich experience from fundamental research, laboratory experiments and the deployment of its technology in real conditions to address new applications. The potential of BOOSTHEAT's thermal compression technology can be appreciated in two ways:

- The diversity of heat sources,
- The diversity of its applications.

This diversity, both in the source and in the application, offers a great potential that is still untapped.



6.1 Heat sources

As shown in Figure 14 (results from experiment), the thermal compressor starts generating a pressure ratio from a hot source temperature equal to 200 °C. In the current design, this pressure ratio reaches acceptable values for hot source temperatures above 450 °C, however heat transfer optimization work tends to reduce this threshold.

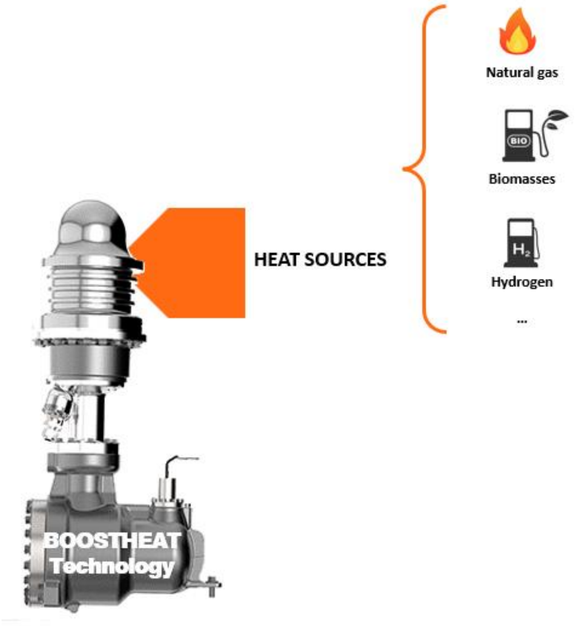
Take Away

The basic operation of thermal compression is obtained from a temperature gradient of more than 180°C between the hot and cold sources.

6.1.1 Combustion

The external heat supply gives the compressor the ability to use heat from any type of fuel: solid, liquid, gas, biomass, etc.

As soon as an external combustion medium can be continuous and controllable (in modulation) it provides the compressor the following advantages:



- Combustion can be properly controlled and the discharge of polluting gases can be considerably reduced,
- There is no explosion or internal combustion: the operation is extremely quiet,
- The torque produced is regular and the mechanical parts are less stressed: this gives the compressor a very long service life,
- The compressed gas is not contaminated by combustion residues.

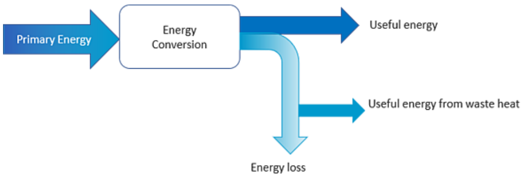
While developing the thermal compressor, the company has demonstrated that its technology works well with gas combustion: methane, propane and biomethane.

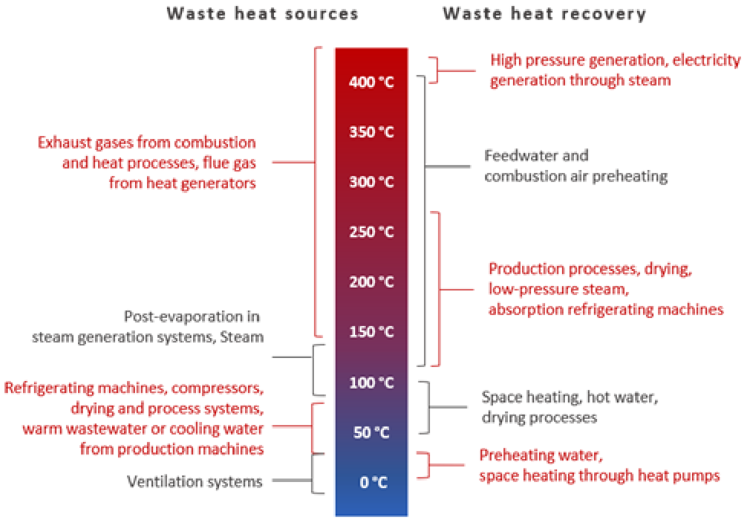
In 2022, the company launched a feasibility study to demonstrate the technology's potential to be adapted to a hydrogen combustion source.

Appendix E "Hydrogen" briefly presents the modifications considered to the existing thermal compressor design. This study confirms that the technology can run with hydrogen without a major redesign, by adapting the insulation and the burner of the existing machine.

6.1.2 Waste heat recovery

Waste heat is the thermal energy indirectly produced by a process, which is neither recovered nor valorized. A large part of this heat can be recovered as useful energy, heat and/or electricity (see 6.3.3 Micro-cogeneration) for internal or external use. The temperature levels of the rejects are variable, with values ranging from 50°C to over 1,000°C.





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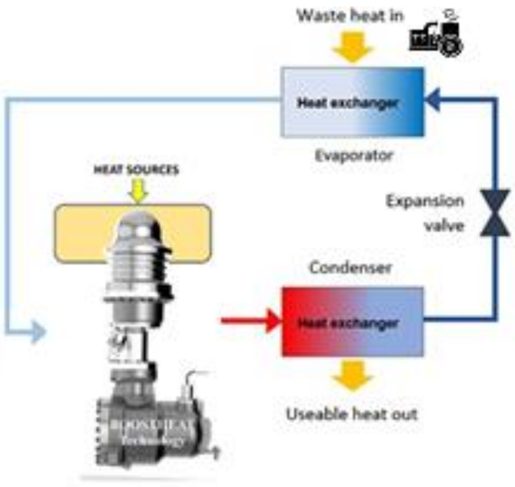
On the technical side, thermal compression does have limitations regarding the compatible heat sources for driving the thermal compressor. However, as shown in the opposite figure, some of the waste heat sources are sufficiently high to be recovered by using a BOOSTHEAT compressor. As this thermal energy is often available and already being paid by the industrial process that generates it, the implementation of an innovative system like BOOSTHEAT to efficiently produce heat and/or electricity (cf. 5.3.3 Micro-cogeneration) allows to minimize the energy consumption and thus the emission of greenhouse gases (GHG).

For low temperature thermal sources, the recovery approach is similar to a standard heat pump, the recovery is carried out through the evaporator.

For high temperature sources, this heat is used directly to initiate the thermal compression cycle, which is not feasible with market solutions. The figure below shows the two possible approaches:

Recovery of high temperature waste heat



Recovery of low temperature waste heat

The following parameters show the level potential of the waste heat sources:

1. The temperature level of the waste heat source.
2. Heat quantity or thermal power available in the waste heat medium.
3. Medium of the waste heat (specific heat capacity and composition).
4. Time availability: continuous or fluctuating, seasonal, number of full load hours per year.

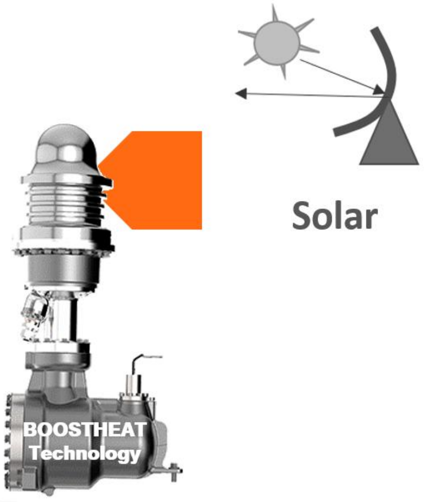
BOOSTHEAT technology is adapted to the direct valorization (heat and/or electricity) of high temperature fields (T > 400 °C) or indirectly via a heat pump cycle (high temperature heating, ...).

Take Away

Thermal compression is worthwhile for industrial companies that want to recover waste heat. On the one hand, the activation of the compression cycle at high temperature provides an innovative, accessible and efficient solution to the challenges of recovering very hot sources. On the other hand, the lifetime and the low level of maintenance inherent to the technology can easily guarantee the ROI of such a solution for an industrial company seeking to optimize its energy consumption.

6.1.3 Use of renewable energies

Because of the external heat input, the BOOSTHEAT technology is suitable for using concentrated solar energy to produce electricity and/or solar cooling by integrating the thermal compressor into a refrigeration cycle.



6.2 Fluids suitable for thermal compression

The original choice of fluid was CO_2. Its advantages are:

- Its low impact on the greenhouse effect: compared to almost all refrigerants except some HFO (hydrofluoroolefin), HC (hydrocarbon), ammonia and dimethyl ether,
- Its cheapness and availability: it is considered as natural, even if it is extracted from the effluents of chemical industries (like the one producing ammonia or bioethanol whose productions generate a lot of CO_2),
- Its non-flammability, its non-toxicity and its chemical stability at high temperatures (up to 1100 K). It has no effect on the ozone layer.

However, CO_2 has some downsides. The main one is that it requires to work at relatively high pressures. This has resulted in a mechanical design that deteriorates the heat exchange between the heat source and the CO_2.

A theoretical study is underway to consider the replacement of CO_2 in the heat pump application by another pure fluid or a mixture of different refrigerants to reduce the mechanical constraints and optimize the exchanges between the heat source and the CO_2.

The criteria for the choice of a new fluid were in the following order:

- No impact on the ozone layer (even negligible),
- GWP ≤ 150,
- Non-toxic,
- Chemically stable when heated,
- Non-flammable for pure fluids and for mixtures (1 mixture may contain a flammable fluid),
- High working pressure lower than that of CO_2,
- Equal or better performance than CO_2.

The only fluids identified that meet all these requirements, except for the last one which has not yet been tested, are mixtures of fluids including CO_2.

For a thermal compression application only intended for the compression of a gas from a "low" pressure to a "high" pressure, our concept is adaptable and has the advantages of reducing the overheating of the compressed gas (this is the role of the regenerators in our compressor) and of not polluting the compressed gas with oil (our compressor does not need oil to operate). Our concept can be adapted to the compression of different gases (nitrogen, hydrogen, oxygen, air ...), as long as the gas is compatible with the materials used in the compressor.

6.3 New possible applications

6.3.1 Gas compression

The main function of the thermal compressor is to increase the pressure of a gas. For example, the compressed air is very present in our daily lives (blowing of the electronic circuitry, textile applications, etc.) and used as source of energy for certain tools (machine tools, braking of heavy trucks and railway locomotives, etc.).

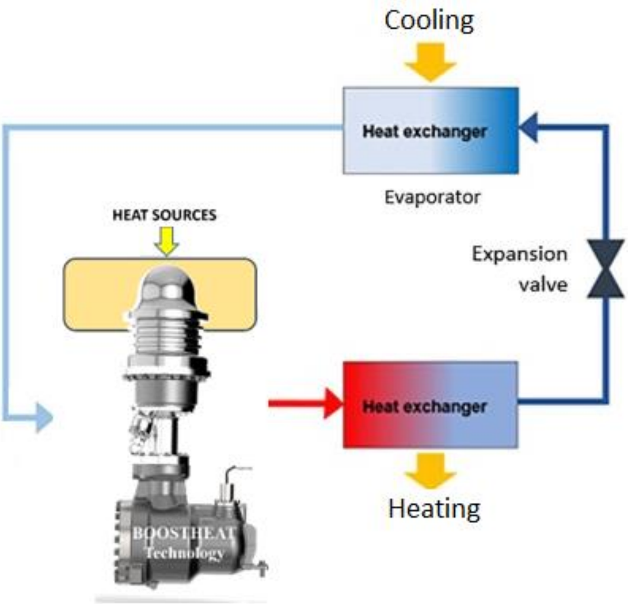
Considering the compatibility of the gas to be compressed with the thermal compressor, this one guarantees its main function of raising the pressure. The BOOSTHEAT thermal compressor can thus be adapted to the compression of various gases (nitrogen, hydrogen, oxygen, air, etc.), as long as the gas is compatible with the materials used in the compressor.

Today's compressors are no longer designed solely to compress a gas to a given pressure. The quality of the compressed gas is also a concern. The absence of lubricating oil in the thermal compressor means that the quality of the compressed gas will be different from the lubricated mechanical compressors ones. This is particularly important in the electronics industry, in nanometric processes, in the medical sector, in clean rooms and in the food industry in general.

Figure 4 in Appendix D (Pressure ratio vs diameters of cold and hot parts in the cylinder) shows the compression ratios involved in the existing thermal compressor and the levels that can be achieved based on numerical models of the technology.

6.3.2 Reversible heat pump

The BOOSTHEAT technology provides possibility to make a reversible heat pump to produce hot or cold according to need, always from a thermal heat source. It is also possible to make negative cold.



6.3.3 Micro- CHP

CHP and CCHP are the extraction technologies of two or three final energies simultaneously, using only one energy source. The final energies are usually the energy carriers, in other words, they are either thermal energies (heat and cold) or electrical energy.

Conventional power plants convert only about 30% of the fuel's energy content into electricity. Highly efficient combined cycle power plants convert around 50% of the available energy into electricity. Other energy losses occur in the transmission and distribution of electrical energy to the individual user. The inefficiency and pollution problems associated with conventional power plants have motivated new developments in on-site electricity generation. The overall efficiencies of central power generation and distributed combined cycle power generation are shown in Figures 17 and 18.

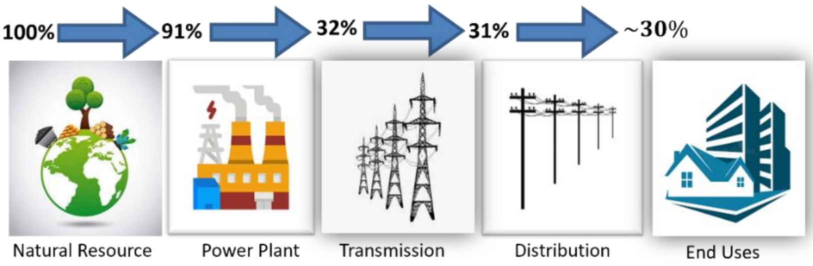


Figure 17. Efficiency of a power plant

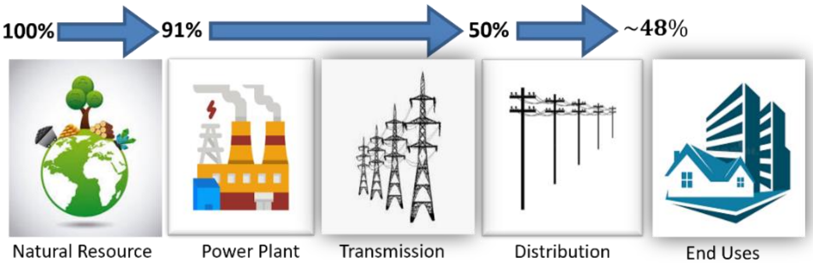


Figure 18. Efficiency of a combined cycle plant

The electricity that reaches the end user can be used to operate central heating and air conditioning systems, electrical appliances, lighting, and in some cases water heater.

These are the same end uses that could be provided by a micro-CHP system with greater overall thermal efficiency. The range of electricity production of a micro cogeneration system is 1 kW to 10 kW intended for residences or buildings where the energy needs (power and heat) are low. Waste heat is also used to meet space heating and DHW needs.

Another advantage of micro-CHP, unlike the common method of electricity production, there are no more losses due to transmission and distribution. Micro-CHP systems can use around 75% of the available fuel energy to simultaneously supply electrical and thermal energy. A micro-CHP system can achieve an overall efficiency of around 75%, while a modern combined cycle power plant will have an overall efficiency of around 50%. The overall efficiency of a micro-CHP system is shown in Figure 19.

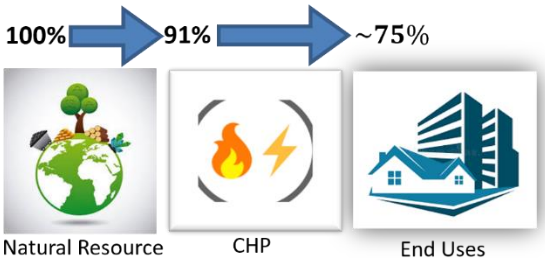


Figure 19. Efficiency of a CHP unit

BOOSTHEAT technology can include micro-CHP and even micro-CCHP technologies. For the realization of this potential, it is possible to convert thermal compression technology into a Stirling engine by adding a working piston.

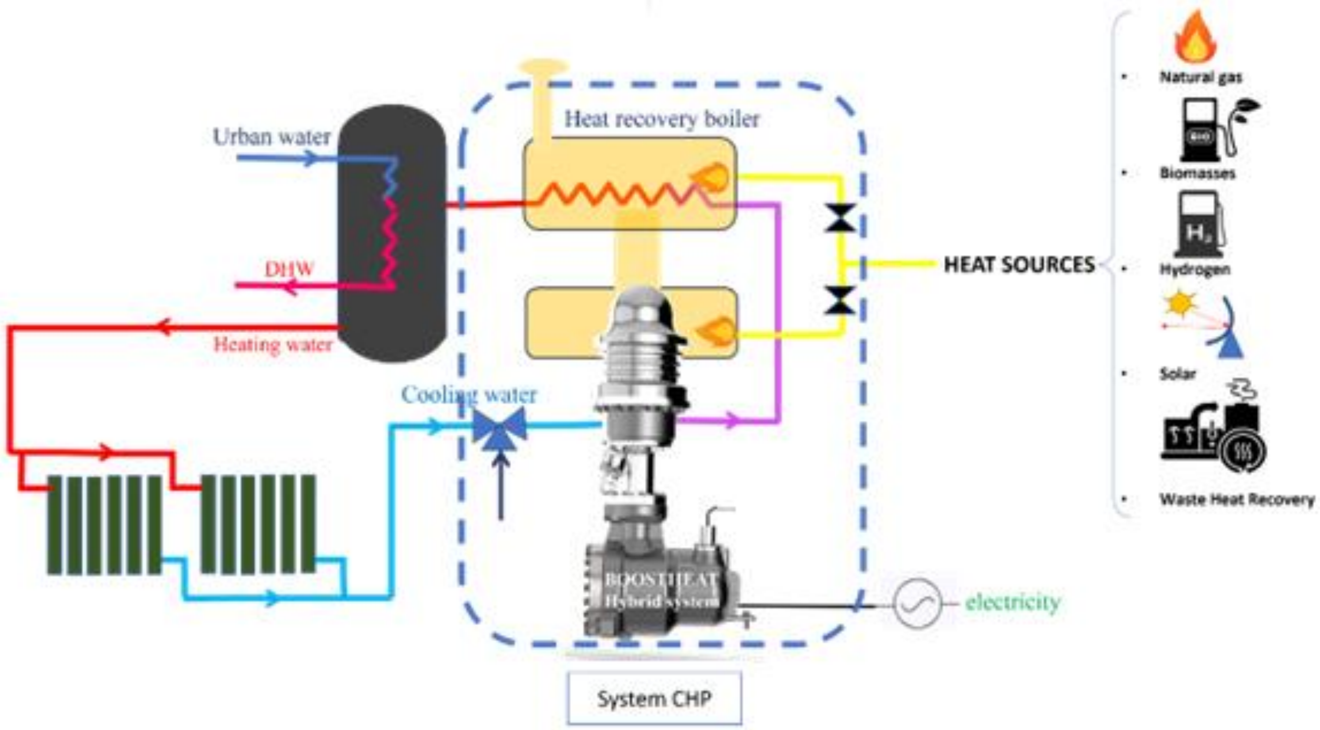


Figure 20. Micro-CHP with BOOSTHEAT technology

The approach of the micro-CHP resulting from a thermal compression cycle was the subject of a patent filed in 2019 by BOOSTHEAT: PCT/FR2020/050464 HYBRID THERMODYNAMIC COMPRESSOR. This patent address both the coupling of thermal and volumetric compressors but also the micro-cogeneration service that can be activated by means of a generator.

7 / CONCLUSION

In the first place, this White Paper outlines the status of the original thermal compressor among thermal machines and highlights the fundamentals of BOOSTHEAT's innovative thermal compression technology. This solution differs from existing technologies by its technological simplicity of implementation and its potential to meet current energy challenges.

To introduce its innovation, BOOSTHEAT has oriented the development of the thermal compressor in the direction of replacing the mechanical compressor in a thermal heat pump cycle (gas-driven) compatible with the domestic heating market, using CO_2 as a refrigerant fluid. It has prioritized its research work to provide innovative answers to the technical challenges related to the development of its technology for industry. In parallel to these activities, the company has continued to patent its concepts in order to remain a forerunner in efficient thermal compression solutions.

BOOSTHEAT has built up its experience in understanding and mastering thermal compression over the last ten years with R&D programs focused on fundamental research, development and reliability of the CO_2 thermal compressor with a view to the industrialization of its natural gas heat pump.

The potential of thermal compression can be expressed in two ways:

- The valorization of different energy sources, made possible by the contribution of external heat,
- The diversity of its applications: gas compression, heat and cold production, micro-cogeneration, etc.

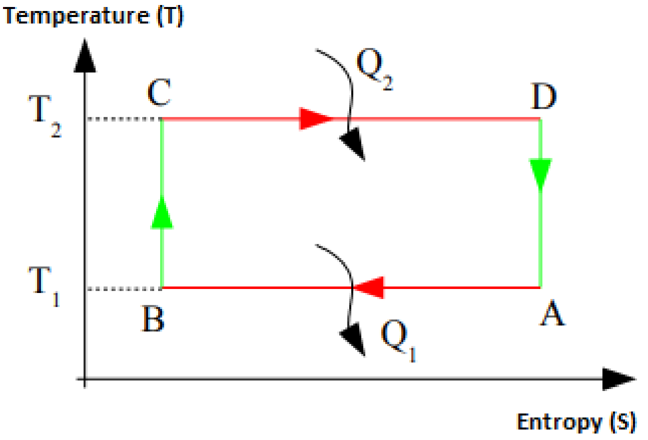
With its industrial experience and aware of the benefits of its technology, BOOSTHEAT enhances the potential of its innovation through new patents and continues its development process focused on the compressor to provide new technical answers to industries facing the urgency of the energy transition.

8 / APPENDIX

Appendix A: Carnot thermal machine

In 1824, Sadi Carnot developed a theoretical thermodynamic cycle whose efficiency of a thermal machine is maximum: this is the Carnot cycle. This cycle is only theoretical and cannot be implemented experimentally because it is considered reversible. It consists of four successive transformations:

- Reversible isothermal compression at cold temperature T_1 (A➔B),
- Isentropic compression (B➔C),
- Reversible isothermal expansion at hot temperature T_2 (C➔D),
- Isentropic expansion (D➔A).



Theoretical cycle of Carnot machine.

The efficiency η of a power cycle operating according to the Carnot cycle is defined as being the ratio of the useful work provided W and the thermal energy received Q_2 :

$$\eta = \frac{useful\ energy\ output}{thermal\ energy\ input} = \frac{W}{Q_2}$$

By combining the equations from the first law and the second law of thermodynamics for a reversible system, the efficiency of a Carnot cycle becomes:

$$\eta = 1 - \frac{T_1}{T_2}$$

This efficiency represents the maximum efficiency that a dithermal machine can achieve. This efficiency is always less than 1 and reaches unity ($\eta = 1$) in the case where $T_1 = 0\ K$.

Appendix B: Stirling engine

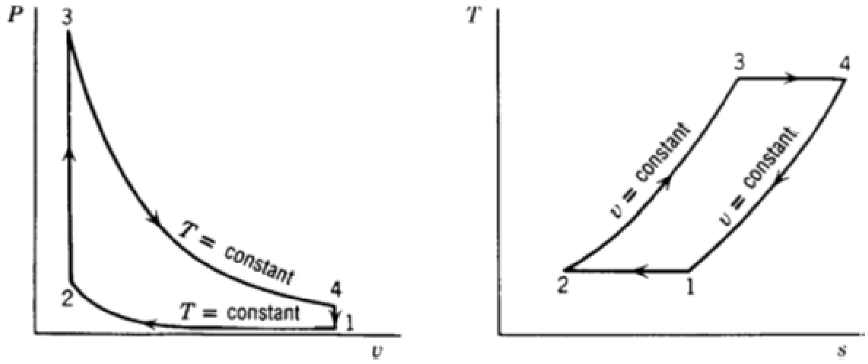
To understand how a Stirling engine works, it may be useful to consider the theoretical Stirling cycle. It is a closed cycle described by four elementary processes. They consist of two isochoric[4] heating and cooling transformations and two isothermal[5] compression and expansion transformations (Figure 3).

1➔2 Isothermal compression: this process consists of a slight compression of the cold gas and a rejection of heat towards the cold source.

2➔3 Isochoric compression: the gas is transferred from the cold side to the hot side. By passing through the regenerator, it receives heat from it and its pressure increases under the effect of heating.

3➔4 Isothermal expansion: the gas being on the hot side, it receives heat from the hot source. Thus, its volume increases and exerts work on the working piston.

4➔5 Isochoric expansion: the hot gas at the end of isothermal expansion is transferred to the cold source. It transfers heat to the regenerator and its pressure decreases due to cooling.



Theoretical Stirling cycle

If the quantity of heat received by the gas during isochoric compression is equal to that which it yields during isochoric expansion (perfect regenerator), then the heat transfers between the engine and its environment consist of a heat input at the temperature of the hot source (T_C) and a heat rejection at the temperature of the cold source (T_f). Under these conditions, the theoretical efficiency of a Stirling cycle is analogous to the Carnot cycle.

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[4] constant volume

[5] constant temperature

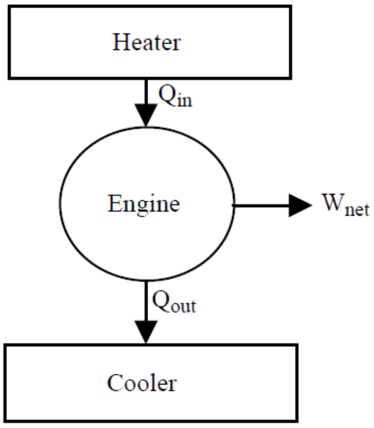
A Stirling engine is a simple external heat supply engine that uses a gas (compressible fluid) as a working fluid.

An energy balance made on a cyclic thermal machine is globally based on the first law of thermodynamic. It gives a conservation of energies between those received and supplied by the machine:

$$Q_{in} = Q_{net} + Q_{out}$$

The thermal efficiency $\eta_{Stirling}$ of the Stirling engine is given the ratio of the useful power and the heat inlet:

$$\eta_{Stirling} = \frac{W_{net}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{T_f}{T_C}$$

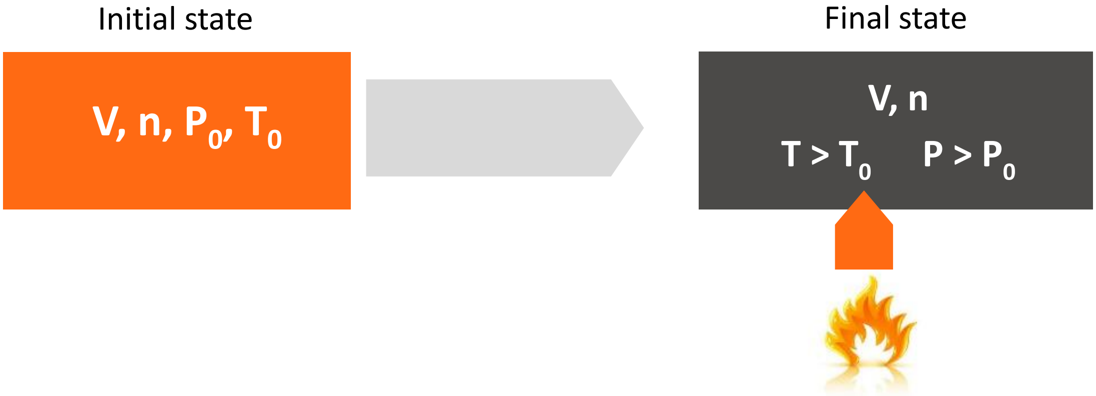


Schematic diagram

Appendix C: thermal compression

Increasing temperature of a gas at constant volume and quantity of matter, leads to an increase in pressure.

For a finite volume *V* containing a quantity of matter *n* of a gas at initial state of temperature T_0 and pressure P_0, the increase in the temperature of this gas by adding heat increases its pressure as shown in the figure next:



Similarly, a system of constant volume *V* containing a quantity of matter *n* of a gas at initial state of temperature T_0 and a pressure P_0, the decrease in the temperature of the gas by cooling lowers its pressure as shown in the following figure:

Existing Technologies

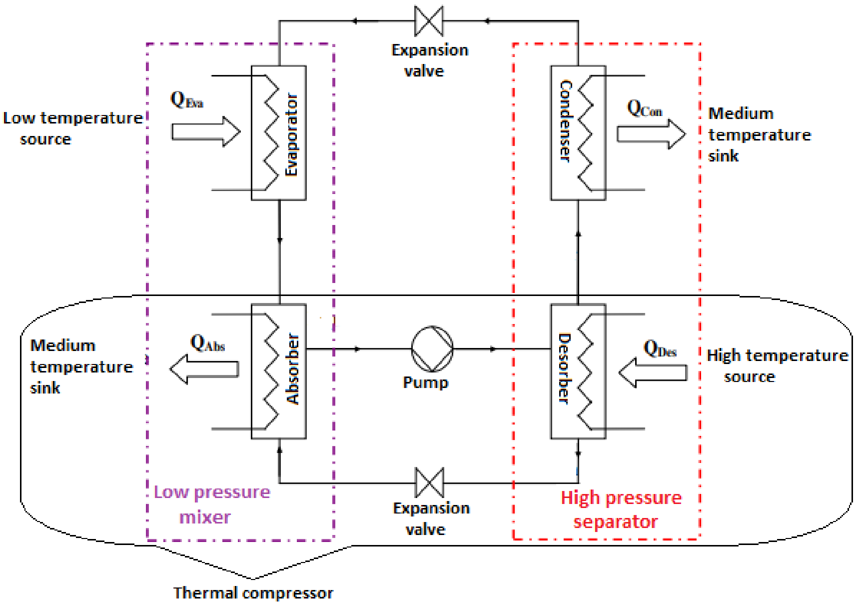
Today, gas compression is mainly based on mechanical compressor technologies (reciprocating piston, screw, scroll, ejector, turbocharger, etc.).

Thermal compression finds technological applications in systems using thermochemical compression. These include sorption (absorption and adsorption) heat pump (HP) systems as well as hydrogen compressors.

Absorption machines

Liquid absorption heat pumps work thanks to the ability of certain liquids to absorb (exothermic reaction) and desorb (endothermic reaction) a vapour. They also use the fact that the solubility of this vapor in the liquid depends on the temperature and the pressure. These machines use as working fluid a binary mixture, one of the components of which is much more volatile than the other and constitutes the refrigerant.

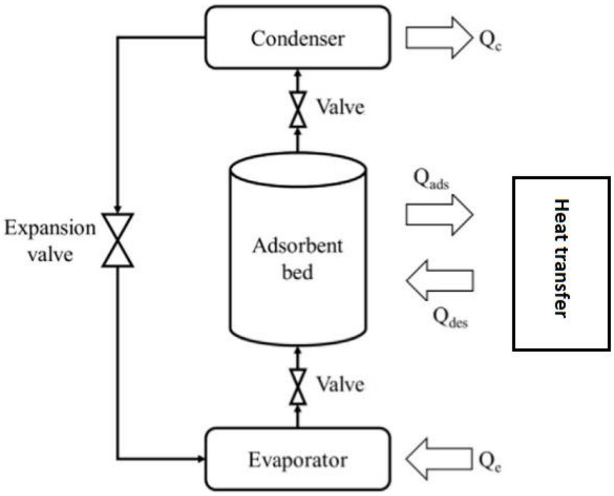
To work an absorption heap pump, heat is used instead of mechanical energy to raise the pressure of the refrigerant. It then clearly appears that the mechanical energy is replaced by thermal energy, hence the qualification of thermal compression machine.



Schematics of common absorption heat pump

Adsorption machines

The physical principle of the adsorption machine is similar to that of absorption machines. Adsorption is the process during which molecules of a fluid (gas or liquid), called an adsorbate, attach themselves to the surface of a solid, called an adsorbent. The adsorption process is depressurization by isosteric[6] cooling, while the desorption process is pressurization by isosteric heating.



Schematics of a common adsorption heat pump

Hydrogen compressor

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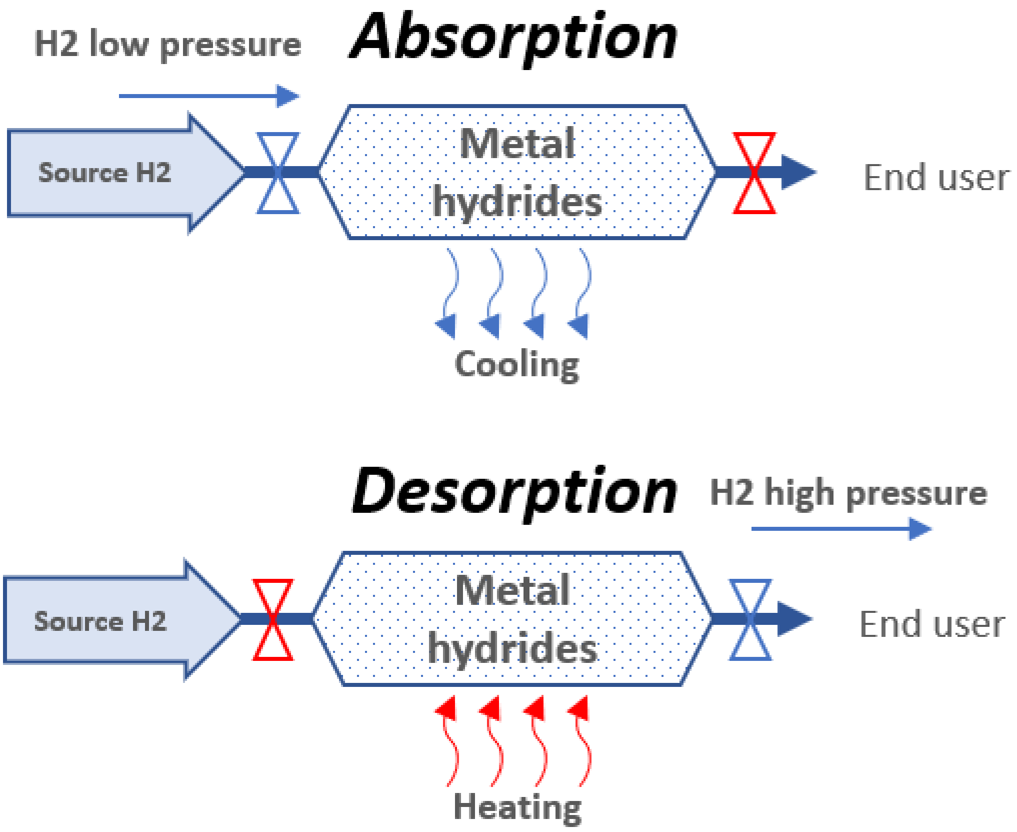
[6] Isosteric: constant matter composition



The European industrial company EIFHYTEC (European industry for Hydrogen technologies) is developing a thermal hydrogen compressor. The technology is based on the thermochemical effect. But the novelty lies in its application to hydrogen. The compression solution is based on an absorption/desorption scenario in a metal alloy.

In the absorption phase, the alloying element subjected to cooling receives hydrogen at low pressure. The molecules will be trapped in the metal hydride. By heating the container, the hydrogen will be released at high pressure [4].

Appendix D: one stage compressor modelling

The working fluid is carbon dioxide (CO_2) which is modelled as a real gas with non-constant thermo-physical properties. In order to describe the behavior of the thermal compressor, the coupled analysis usually applied for Stirling engine modelling is used. This analysis is more accurate than the others but it requires a higher computing time. The compressor stage is divided into several control volumes as shown in Figure 1. Each cold and hot part of the cylinder acts as one control volume. The heat exchangers are divided in a lot of sub-volumes. The dead volume between the regenerator and the cooler is also divided in several control volumes. The number of control volumes depends on the temperature gradients in the heat exchanger considered and on the size of the heat exchanger. The number of control volumes is a compromise between accuracy and computing time. The fluid physical properties at the outlet of each control volume are the ones at the inlet of the adjacent control volume. Some usual assumptions are used:

- There is no leak of the working fluid,
- The hot and the cold parts of the cylinder, and the hot and cold dead volumes are adiabatic,
- The instantaneous pressure in every control volume is the average of the pressure of the control volume interfaces,
- The temperatures of the wall of the heater and the cooler are constant,
- Fluid kinetic energy is negligible; Fluid flow is mono-dimensional.

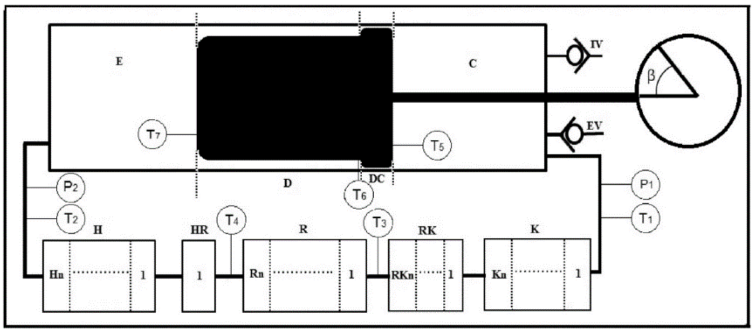
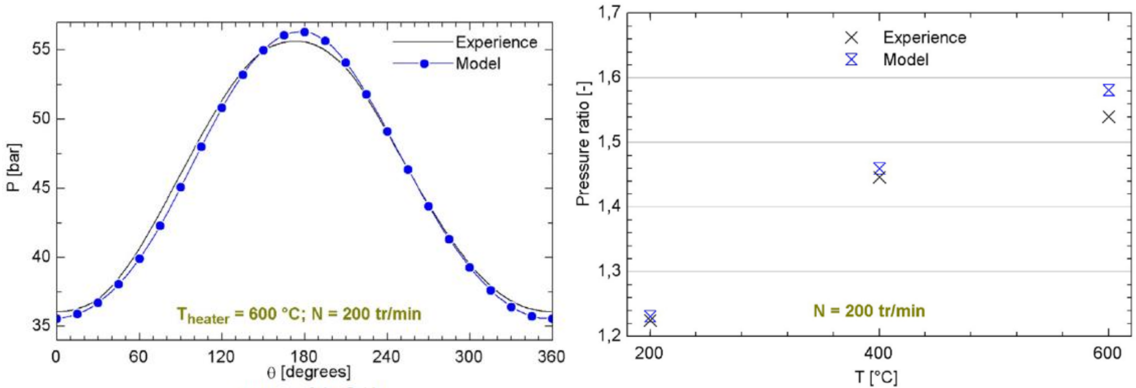


Figure 1. Control volumes of the compressor with instrumentation

The model validation is based on experimental measurements on the thermal compressor prototype. Figure 1 shows the thermal compressor with instrumentation. The work bench is equipped with thermocouples to measure temperature, and pressure transducers to measure the pressure at state points used in the model validation.

The external heat supply at the heater is achieved by an electrical resistance using a heating wire while the cooling process in the cooler is provided by a water circuit. During these experiments, the inlet and exhaust valves where blocked in closed position. As a consequence, no compressed CO_2 is delivered by the thermal compressor.

Figure 2 presents a comparison between the calculated and the measured instantaneous pressure in the cold part of the compressor cylinder. A better agreement is obtained during the expansion phase, which could mean that the cylinder adiabaticity assumption is better observed during expansion than compression.



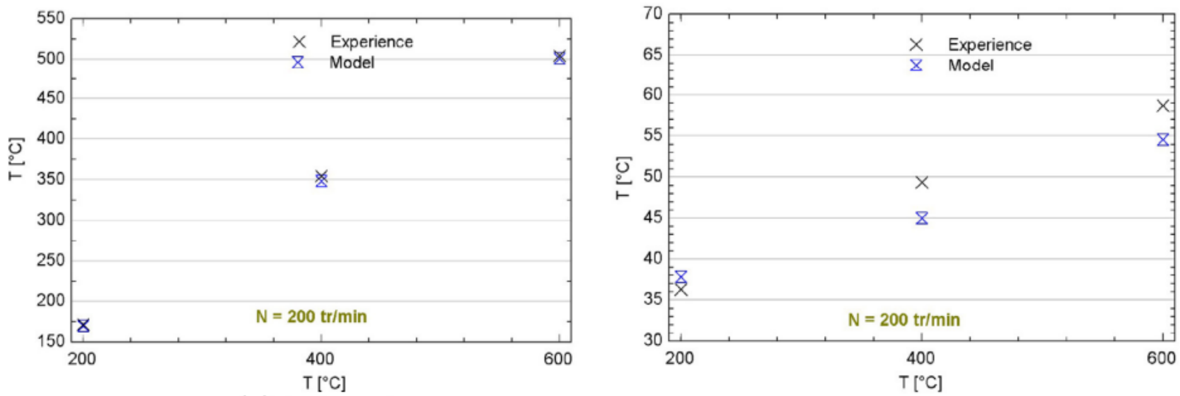
Pressure of the fluid.

Pressure ratio as a function of the heater wall temperature.

Figure 2. Cyclic pressure of the fluid and pressure ratio

The pressure ratio is defined as the ratio between the maximum and minimum pressure over a cycle. The figure shows also the pressure ratios that are quite well predicted.

On the other hand, the modelled and experimental cycle averaged temperatures are in good agreement (Figure 3). Other comparisons between simulation and experiments results for different operating frequencies have shown similar agreements. The model can thus be considered as a good description of the thermal and thermodynamic behaviour of the thermal compressor.



(a) hot part

(b) cold part

Figure 3. Cycle averaged temperature as a function of the heater wall temperature

One’s the model was validated by experimental results; an optimization study of the compression cycle shows that it is possible to reach pressure ratios higher (>3) than that obtained with the current geometry (~1.8). Show figure below.

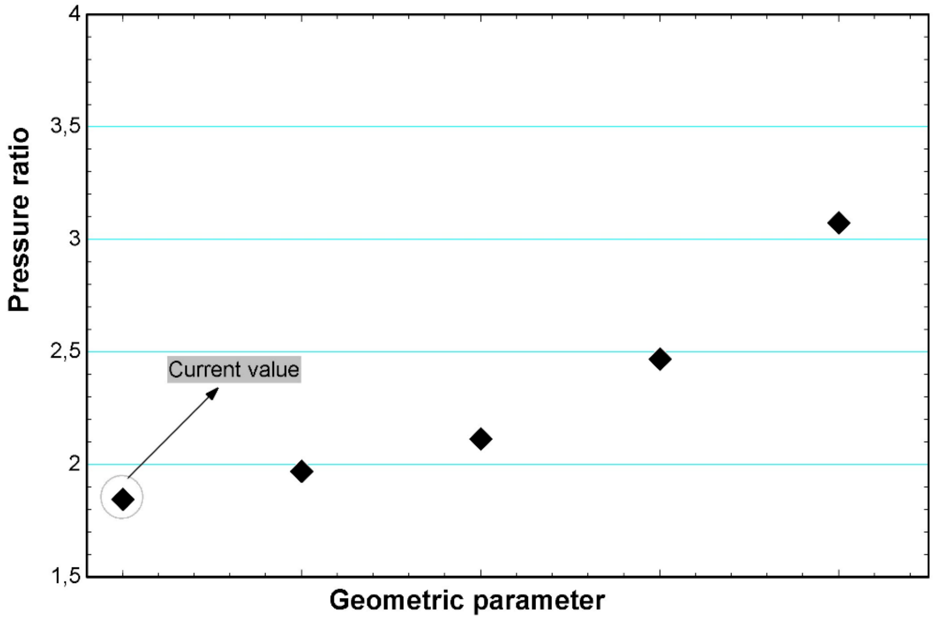


Figure 4. Pression ratio vs diameters cold and hot parts of the cylinder

Appendix E: Feasibility study of a hydrogen fueled porous burner

Thermal compression is a technology requiring heat input via a hot source. Historically a hydrocarbon flame has been used to provide this energy, like a propane flame. However, other heat sources can be used to produce the thermal compression. Thus, a feasibility study was undertaken to set up a hydrogen flame.
Hydrogen has several advantages over traditional fuels. It has a higher energy density and does not emit CO_2 during its combustion. The feasibility study was entrusted to a manufacturer specializing in hydrogen burners: Promeos. The following report is the outcome of this study. It presents the challenges of a hydrogen burner and the modifications to be made to the BOOSTHEAT system for the installation of an H_2 burner.

A. Components

The results of system design calculations are summarized in this chapter. The proposed system architecture is presented in the P&I diagram in Figure 1.

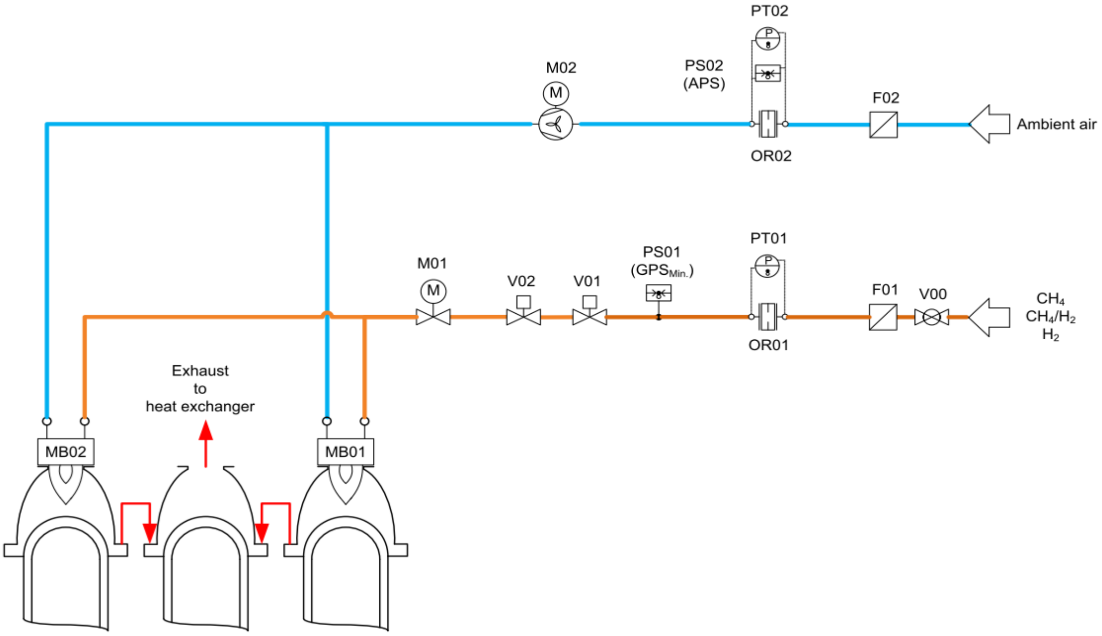


Figure 1. P&I diagram for possible air/fuel supply and control configuration

1. Blower

Blower should supply in whole modulation range combustion air to the system. The air flowrates for fuels having different hydrogen content are similar. A blower able to supply air between 2-12 m^3/h (nominal) will be necessary for this application.

To determine the pressure head needed to overcome pressure drop in the system, a pressure drop estimate estimation done on the air line (see Figure 2).

Assuming a pressure drop of approximately 20 mbar on exhaust line and 10 mbar orifice pressure drop for flow measurement, a blower having a pressure head of approximately 50 mbar at 12 m^3/h will be necessary for this application.

The blower muss be regulated via an rpm-controller to control air volume.

2. Filters

Burner ceramic has fine ceramic pores which could be clogged with particles in the ambient air, therefore an air filter with a filter class F7 is to be installed before air blower.
On the gas line a common mesh type filter is adequate for household applications.

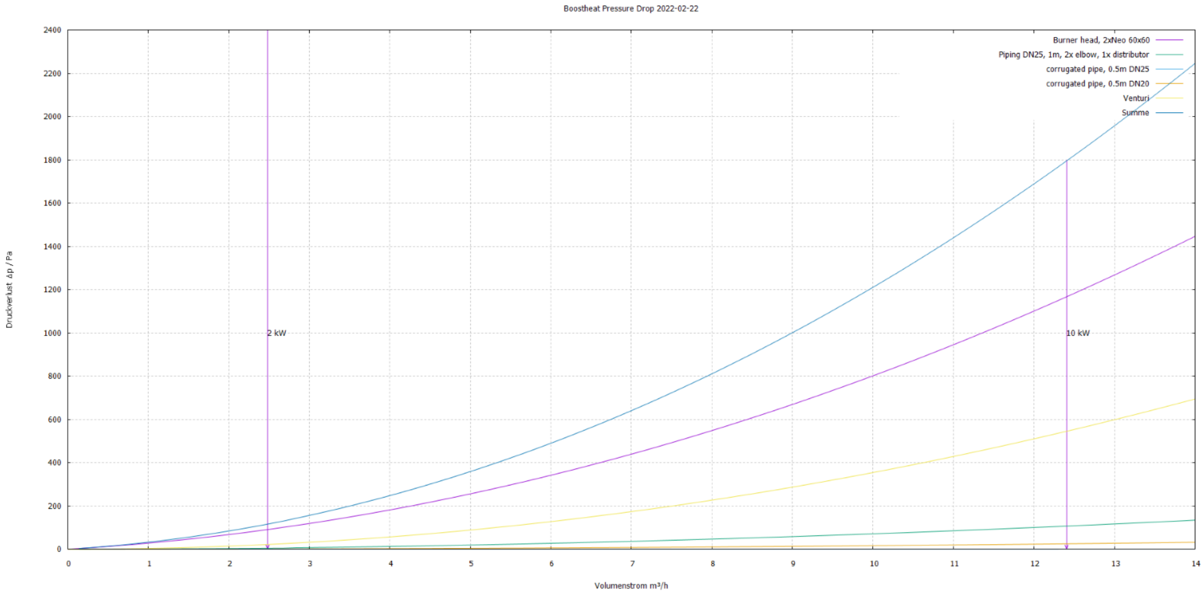


Figure 2. Calculated pressure drop on air line (fuel: natural gas-H, without pressure drop in exhaust)

3. Pressure sensors and switches

According to thermo-process standards gas and air pressures are to be monitored. On air line an air pressure switch monitors the pressure drop over air orifice which ensures the lower flowrate on the air line.

On the gas line the minimum pressure will be monitored with a switch.

Differential pressure sensors are needed to measure and control air and fuel flowrates.

4. Gas shut-off valves and flow regulation valve

Two safety shut off valves (class-A valves) are necessary to seal the gas line in accordance with standard leakage values.

B. Burner Design

Heat Demand and Output Density

- The burner geometry is chosen according to heat density on the burner.

Flame stabilization – burner ceramic design

- Hole geometry (diameter, length and number of holes),
- Flame stabilization cone (flame propagation speed = mixture speed).

Ignition and Flame Detection

- UV-sensor flame detector,
- Ignition via electrodes.

Burner Integration

Below are pictures of 3D-desing study, where a specific burner Is integrated on heat pump dome.

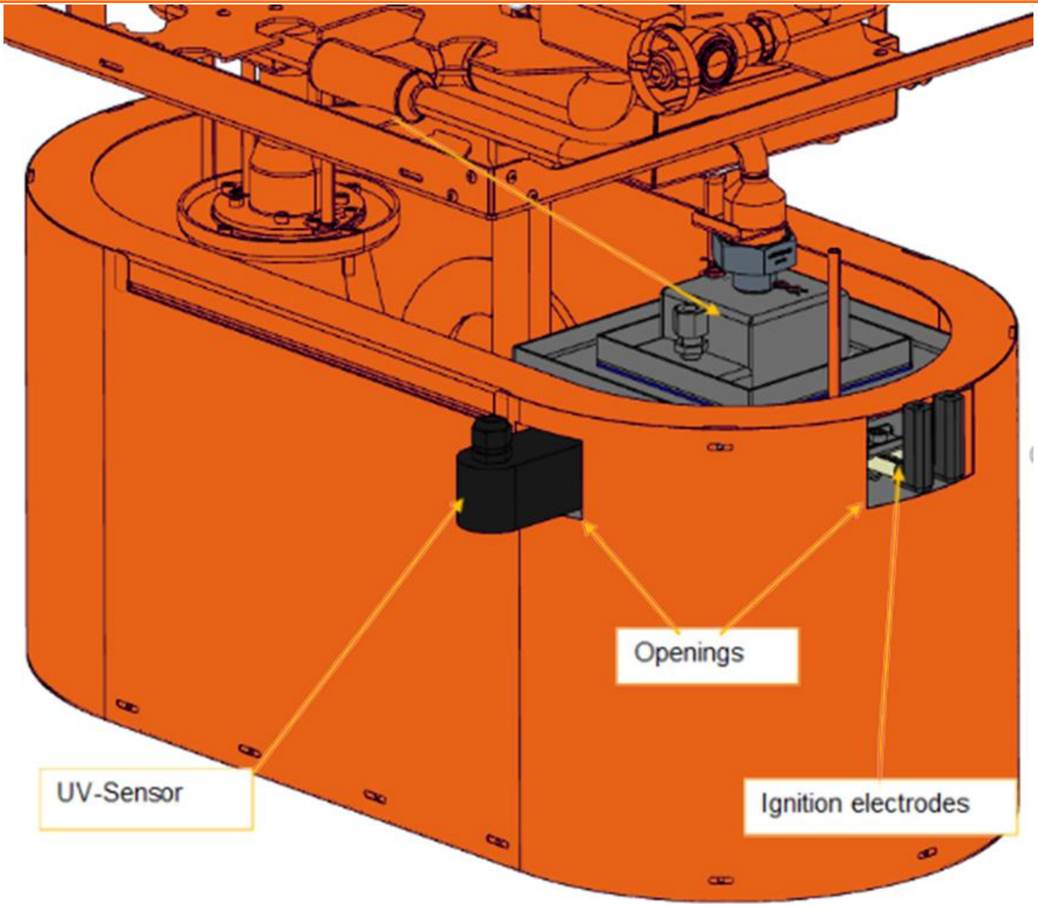


Figure 3. Burner unit on heat pump

This study shows that the BOOSTHEAT thermal compression technology is compatible with a hydrogen burner. The installation of a new flame control system and additional insulation in the combustion chamber will be the two aspects requiring the most work. Nevertheless, it is reasonable to consider that thermal compression can be activated by a hydrogen flame in the configuration offered by BOOSTHEAT.

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