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# Modelling of a new thermal compressor for supercritical $CO_2$ heat pump

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A B S T R A C T

A new concept of thermal compressor has been designed by the boostHEAT company. This compressor uses thermal energy provided through the heater instead of mechanical energy to increase the pressure of the heat pump working fluid. The compressor is made up by the following parts: a cylinder with a displacer piston, a heater, a regenerator and a cooler. The heater is connected to the hot part of the cylinder on the one hand and to the regenerator on the other hand. The cooler is connected to the regenerator on the one hand and to the cold part of the cylinder on the other hand. The cold part of the cylinder is connected to the low pressure branch of the heat pump (evaporator) through an automatic inlet valve, and to the high pressure branch of the heat pump (gas cooler) through an automatic exhaust valve. The compressor is intended to replace the conventional mechanical compressor in a $CO_2$ heat pump for the residential heating or combined heat and power market. The main feature of the system is that the working fluid of the thermal engine for compression is the same as the working fluid of the heat pump. The principle of the new thermal compressor and its advantages for heat pump application will be briefly presented. A model of the thermal compressor has been developed and validated. Modelling results related to the regenerator, the piston rod diameter, the size of the adiabatic dead volumes and the working fluid leaks in the annular gap between the cylinder liner and the piston are presented.



## 1. Introduction

The building represents a major energy consumption. For example in France, this sector consumes 44% of the total energy and accounts for 25% of the greenhouse gas emissions. Heating alone accounts for 70% of the total energy consumption of the buildings [1]. Heating is therefore an important field of energy savings. Efforts focusing on improving the energy efficiency of heat production devices will have a decisive impact on the level of fuel consumption and on the reduction of greenhouse gases emissions.

Low temperature heat production devices from a heat source such as oil or gas combustion, combined with a heat pump effect (free energy taken from the environment) provide a significant improvement of the energy efficiency of the fuels. These technologies are very important issues for our societies. The underlying thermodynamic principles of these systems, generically known as trithermal systems, demonstrate an increased energy efficiency for applications in heat production compared to the conventional boiler. However the commercial use of trithermal systems remains very limited. Amongst the trithermal systems it is worth mentioning non-integrated devices such as the coupling of a gas engine with a conventional vapor compression heat pump, the coupling of a Stirling engine with a conventional vapor compression heat pump or with a Stirling heat pump, or integrated devices such as the absorption or the adsorption heat pumps or the Vuilleumier machines.

On the other hand environmental concerns have conducted to the banishment of some refrigerants and $CO_2$ tends to become more and more used as the best alternative [2–4]. The use of a transcritical cycle has emphasized the development of refrigerating machines or heat pumps using $CO_2$ as the working fluid [5–8].

The concept developed by the boostHEAT company and presented here is quite new and original. It consists in an integrated trithermal system combining a thermal compressor and a conventional vapor compression heat pump. The thermal compressor is identical to a gamma type Stirling engine of which the power piston and cylinder have been replaced by automatic inlet and exhaust valves.

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## 2. The new thermal compressor

### 2.1. Principle of the thermal compressor

From the mechanical point of view, the thermal compressor is made up by the following components as it is illustrated in Fig. 1: 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*).

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 compressor 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. In particular, this feature allows the absence of any mechanical compression and power transmission device. The heat driven compressor performs a mechanical work of compression on a fluid (volumetric compression: suction-compression-discharge) 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. Indeed the pressure differential is almost zero in the case of a displacer. Such a heat driven compressor is thought to be very convenient to replace the mechanical compressor of a conventional transcritical $CO_2$ heat pump. So the fluid in the compressor will be $CO_2$, which is the most promising fluid for domestic heat pump applications. Modelling results show that for $CO_2$ heat pump applications a two stage thermal compressor is needed. The thermodynamic cycle described by one stage of the thermal compressor is made up of four processes:

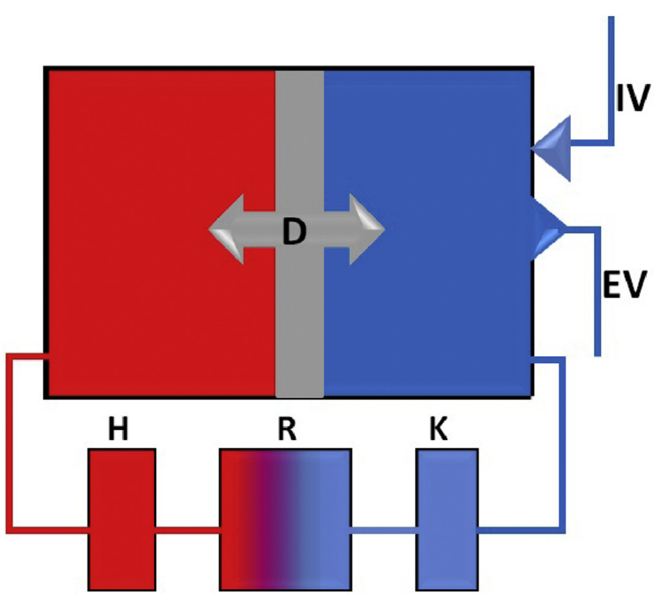


**Fig. 1.** New concept of thermal compressor for supercritical $CO_2$ heat pump application.

- An isochoric compression 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 $P_1$ 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 $P_2$.
- An isobaric exhaust. At pressure $P_2$ 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 centre.
- An isochoric expansion 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 $P_2$ up to pressure $P_1$.
- An isobaric sucking. At pressure $P_1$ 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 centre.

### 2.2. The model

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 behaviour of the thermal compressor, the coupled analysis usually applied for Stirling engine modelling is used [9,10]. 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 Fig. 2. 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 [11]. 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.

According to the assumptions the coupled analysis is based on the equations for mass and energy balance on each control volume. The fluid flow rates are assumed to be positive if the fluid moves from the cooler to the heater. At the interfaces of a control volume the fluid rate is assumed to be positive if it comes out and negative if it comes in. The flow rate in a control volume is given as a function of the two flow rates at the right and left interfaces:

$$\dot{m}_i = (\dot{m}_l - \dot{m}_r)_i/2 \quad (1)$$

The conservation of mass is given by:

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