Novel heat engine:
Regenerative heat to mechanical energy converter with a dense working fluid

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***Regenerative heat to mechanical energy converter with a dense working fluid* is a simple and economical alternative to state-of-the-art types of heat engines in power range up to several MW. Being an external combustion engine the converter can use heat of any grade and origination – from heat of combustion of fossil and bio fuels, solar energy to a low grade heat sources typical of Organic Rankine Cycle (ORC) engines. Various safe and environmentally friendly liquid working fluids such as water or carbon dioxide can be used in the engine. The engine is noiseless. The operation of the engine is based on a unique cycle having the same efficiency as Carnot cycle and very simple, reliable and inexpensive design. As a result cost per kW of the engine is much lower compared with that for contemporary internal combustion, Stirling and Rankine engines.**

A large-scale deployment of micro and mini distributed generation and cogeneration is delayed now by a lack of a suitable prime mover (heat engine). The great majority of power in range up to several MW today is generated by internal combustion (IC) engines since they are the cheapest and most efficient prime movers in this power range. However being heat engines in theory, they cannot use available heat sources directly – actually they consume only more and more expensive hydrocarbon fuels – gasoline, diesel fuel etc. They have the highest emissions among all types of prime movers and the shortest life time; they are not suitable for unmanned remote operation.

However external combustion (EC) engines such as Rankine and Stirling ones in this power range are too complicated and expensive; they also suffer from high dead volumes and heat losses lowering efficiency as well as non-resolved problems with lubrication and sealing in severe conditions of high-temperature working fluids. That is why the steam engines were totally displaced by IC-engines several decades ago, whereas the Stirling engines never became competitive in mass market.

The converter is an external combustion engine with a *dense working fluid* which is liquid at the low cycle temperature and gas or supercritical fluid at the highest cycle temperature. As a result all rubbing and sealed parts of the converter operate in liquid having better lubricating and friction heat rejecting ability. Moreover liquid working fluid permits to use hydrostatic fluid bearings eliminating any rubbing friction and wear at all.

Being external combustion engines the converters can use any kind of heat sources including solar and geothermal energy and combustion heat of unconventional, sustainable and low-grade fuels such as biomass and biomass-derived fuels and waste.

The use of liquid working fluid rather than gases has several advantages:

- a very high power density and torque
- sealing of liquid to prevent working fluid leakage is easer;
- liquid, being incompressible, decreases remarkably the adverse effect of dead volumes;
- liquid working fluid facilitate heat exchange
- liquid working fluid make the converter much safer since in operation volume of gas/vapor phase is smaller whereas out of operation a high-pressure gas phase can be absent at all.

These advantages in combination with a unique cycle permit to develop a very simple, inexpensive, robust and safe design.

The basic principle of heat to shaft power converter shown schematically in Figure 1. The converter consists of a differential cylinder 1 with a differential piston 2 inside. The lower part 2a of the piston serves as a power piston; the upper part 2b plays a role of displacer.

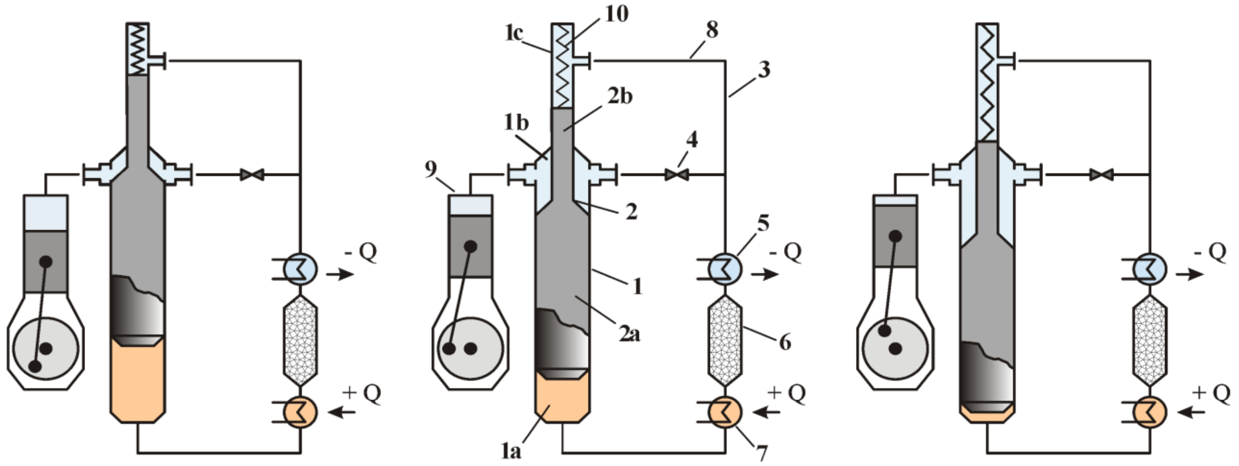


Figure 1

The piston 2 divides the internal volume of the cylinder into three parts: a hot part 1a, a cold power part 1b and a cold displacement part 1c. The hot part 1a and the cold power part 1b are communicated by a heat circuit 3 which includes a shut-off valve 4, a cooler 5, a regenerator 6 and a heater 7. The cold displacement part 1c is communicated to the heat circuit 3 in between the valve 4 and the cooler 5 by a displacement line 8. A spring 10 tends to keep the piston 2 in the middle position.

A piston hydraulic motor 9 shown schematically is connected by a pipe to the cold power part 1b of the cylinder. Instead of the reciprocating motor oscillating or rotary hydraulic motors can be used.

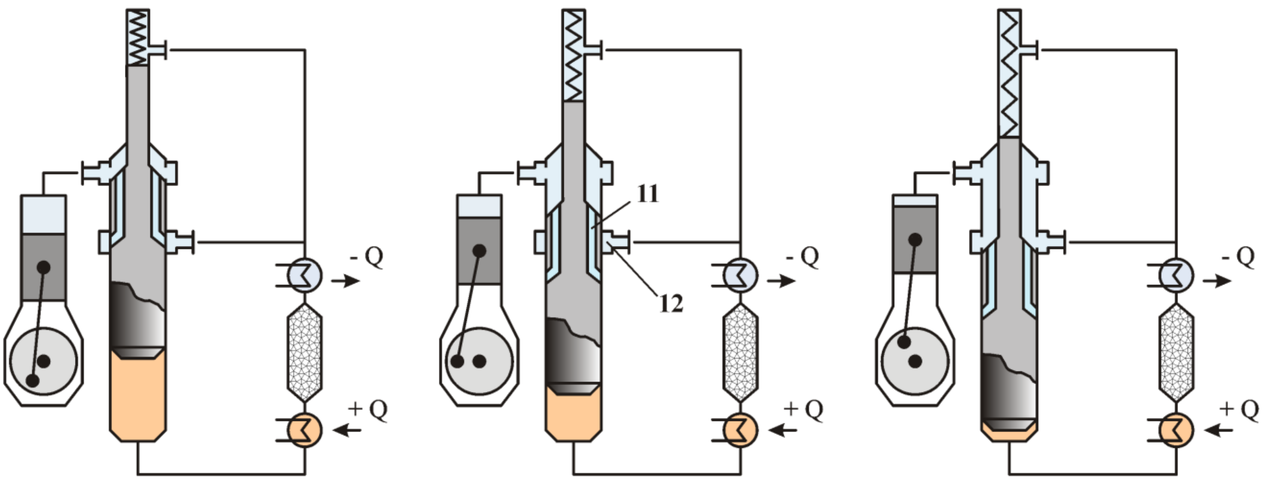
All the installation is filled with a liquid working fluid. At the beginning of the operation the valve 4 is closed. As soon as a heating and cooling are arranged the liquid working fluid is heated and boiled in the heater 7. Pressure in the hot part 1a of the cylinder and the heat circuit rises, the piston 2 moves up displacing the working fluid from the cold power part 1b, compressing the spring 10 and driving the hydraulic motor 9. At the same time the piston 2b displaces the working fluid from the cold displacement part 1c of the cylinder to the heat circuit 3 and then to the hot part 1a. The working fluid heated and evaporated in the regenerator and the heater maintains a high pressure in the hot part and heat circuit during the compression stroke.

In the upper limiting position of the piston (Figure 1a) the valve 4 opens equalizing pressure inside the engine. During this pressure equalization step the working fluid continues to boil in the heater and flows through the regenerator and the cooler, where it cools and condenses, to the cold power part of the cylinder and then to the hydraulic motor.

When pressure in the hot and cold parts is equalized the spring pushes the piston down and the valve closes. The moving piston displaces the working fluid from the hot part to the regenerator and the cooler and then to the displacement part. Cooling and the following condensation in the regenerator and cooler result in a pressure decrease in the hot part and further movement of the piston down. The piston sucks the working fluid from the hydraulic motor.

In the lower limiting position of the piston (Figure 1c) the valve opens again equalizing pressure in all parts of the engine. After that the spring pushes piston up, the valve closes and the cycle repeats itself.

The power piston itself can play the role of the valve. Such a design is especially convenient for small and medium-size converters. An example is shown in Figure 2 where the piston is in an intermediate and two limiting positions. Passages 11 machined inside the power piston and an additional port 12 form a valve communicating the hot and cold parts of the cylinder at the limiting positions of the piston.



a b c

Figure 2

A working fluid of the converter (water, propane, carbon dioxide etc) could be not suitable for various hydraulic motors that could be powered by the converter. The converter can be combined with oil-based motor by the use of a diaphragm unit separating the liquids and transmitting power between the liquids as shown in Figure 3.

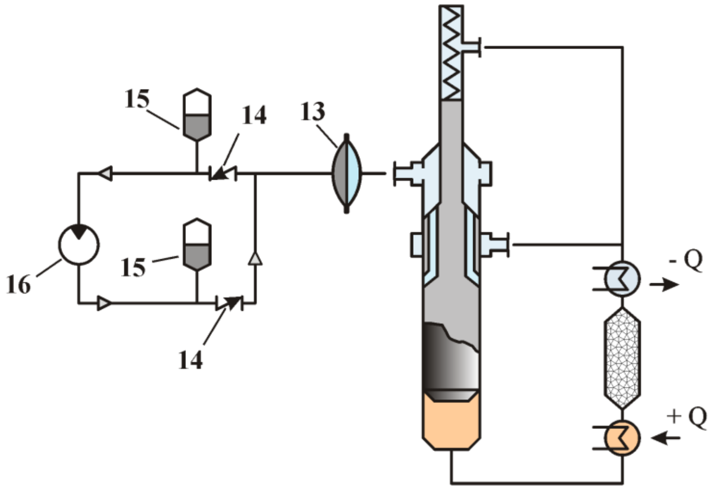


Figure 3

The heat to shaft power converter shown in Figure 3 includes a separating diaphragm unit 13 and an oil power loop containing two check valves 14, hydraulic accumulators 15 and a hydraulic motor 16. The diaphragm unit separates the liquids and transmits power between the liquids. The hydraulic accumulators 15 provide a pulseless flow of oil and a constant pressure drop through the hydraulic motor.

The diaphragm unit can also be used to pump liquids and gases instead of application of more expensive and less energy efficient crank gear- based hydraulic mechanisms typical of diaphragm compressors and pumps driven by electric motors. An example of such an installation is shown in Figure 4.

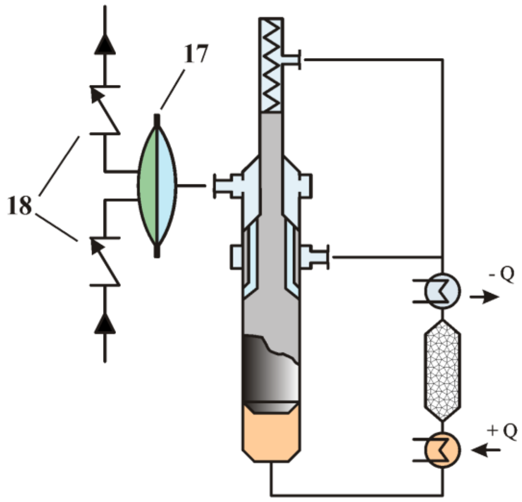


Figure 4

In the compressor shown in Figure 4 a working fluid of the converter actuate a flexible diaphragm in a diaphragm unit 17 provided with suction and discharge valves 18. The unit pumps liquids or compresses gases (shown in green).

Such compressors and pumps can be driven by any source of heat instead of electric motors. In this case expensive variable speed motors with frequency controllers are replaced with simple regulated heat supply (supply of fuel gas, thermal oil, wasted steam etc).

The use of water or carbon dioxide as the working fluid in converters with a diaphragm eliminates a contamination of a pumped fluid. This is especially interesting for pumping and compression in electronic, food industry etc.

The types of heater, cooler and regenerator of the converters proposed depend on the origin and grade of heat source and sink, power range, type of working fluid and so on.

An advantage of the hydraulic output is the highest energy density and torque. For instance, water hydraulic motor with maximum shaft power of 5 kW consumes 24 l/min of water at pressure of 160 bar and has mass only 2.2 kg. Oil-based hydraulic motors can be even more compact and energy dense.

Another advantage of hydraulic output is ability to transmit power to some distance. That makes it possible to dispose the power generating and power consuming parts of the system in most convenient places as well as increase power by a simple multiplying number of the converters working for one main hydraulic line.

And finally several engines with hydraulic output can be easily balanced providing a vibration free, quiet operation.

The heat to mechanical energy converters proposed can cover power range from several watts to several megawatts per cylinder. They can be used as prime movers in micro-, small- and medium- CHP installations, as propulsion engines for cars, trucks, ships, locomotives, and power sources for compressors, pumps, mining machines, vibrators etc.

Being external combustion engines the converters can use any kind of heat sources including solar and geothermal energy and combustion heat of unconventional, sustainable and low grade fuels such as biomass and biomass-derived fuels and waste.