Heat Powered Water Pump for Reverse Osmosis Desalination

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ABSTRACT

Current desalination techniques are typically very energy intensive: energy consumption can account for up to 70% of the desalination costs. To improve economics of water desalination plants innovative energy efficient, inexpensive, water pump powered by heat is proposed. The technology is an alternative to the reverse osmosis water desalination processes. It eliminates electricity consumption and the high-pressure pumps and permits improvements in the energy recovery. Instead of the use of positive displacement (plunger) pumps the pumped fluids (water) are compressed directly by heat in the heat driven pumps (or compressors) and the energy of the working fluid is directly transmitted to a liquid to be pumped. The pump can be powered by any source of heat, e.g. solar, geothermal, waste, combustion. A substantial improvement of the economics of the reverse osmosis processes is expected due to the use of renewable energy, considerable decrease of capital cost, increased energy conversion efficiency and reduced maintenance cost.

Keywords: water pump, desalination, reverse osmosis, energy conversion, renewable energy.

1 INTODUCTION

Reverse osmosis (RO) is one of the most widely employed technologies for water desalination. A drawback of this technology is high consumption of electricity by electric motors used for high-pressure water pumping. Energy consumption can account for up to 70% of the desalination costs. Due to the high energy intensity the carbon footprint of desalination processes is substantial. Modern seawater desalination RO plants emit between 1.4 and 1.8 kg CO_2 per cubic meter of produced water [1, 2].

High capital costs due to expensive high-pressure water pumps and concentrate water energy recovery systems such as pressure exchanges, or Pelton turbines is another drawback.

Most of pumps and compressors including those used in RO desalination plants are driven by electric motors or internal combustion engines (diesels, gas turbines). Therefore compression and pumping are always associated with multiple energy transformations. Pumping systems account for nearly 20% of the world's electrical energy demand and range from 25-50% of the energy usage in certain industrial plant operations [3].

2 HEAT DRIVEN PUMP

To improve economics of water desalination plants innovative energy efficient, inexpensive, robust water pump powered by heat was proposed. It is based on the adaptation of novel heat to mechanical energy converters (engines) [4] for the water pumping application.

2.1 Engine principle

The basic principle of the pump (or engine) is the same as that of regenerative type external combustion engines with closed cycle – working fluid expands when it is heated and contracts when it is cooled. Regeneration of heat makes pumps of this type very energy efficient. The novelty of the pump comprises a new working cycle in combination with the use of a dense working fluid which is liquid in the cold space of the pump and gas or supercritical fluid when it is heated in the hot space of the pump. The working fluid of the engine has very high thermal expansion, yet low compressibility when it is in liquid phase. Carbon dioxide, water-alcohols mixtures or mixtures hydrocarbons can be used as the working fluids.

Specifically the following ideas are implemented in the engine design and operation:

- Phase-change working fluids. This allows solving the engine sealing problem; moreover liquid serves as lubricant and coolant for rubbing and sealed parts; the liquid decreases remarkably dead volumes and their adverse influence on the power.
- The use of new simple compression-expansion cycle without multiple expansion and/or intermediate steam reheating.
- High piston force, torque and power because of the high pressure change during the cycle.
- Low rubbing speed of moving parts. This allows using cheap contactless seals and hydrostatic bearing; thus wear can totally be eliminated and engine lifetime can substantially be increased.
- Hydraulic power output.

The simplified basic principle of the pump is shown in Figure 1. The pump consists of a cylinder 1 with a displacer

2 inside. The displacer 2 reciprocates inside the cylinder by means of an actuator (crank gear) 3.

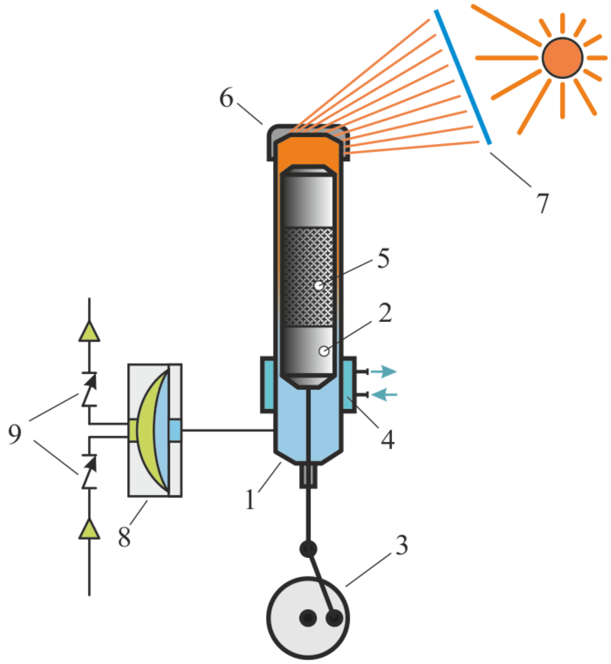

Figure 1: Basic principle of the heat driven pump.

The displacer divides the internal volume of the cylinder into two parts: a hot upper part (shown in orange) and cold lower part (shown in light blue). The pump also includes a cooler 4, a regenerative heat exchanger (regenerator) 5 which is a part of the displacer and a heater 6.

The regenerator 5 represents well developed surface due to numerous micro fins. The cooler can reject heat to water (producing hot water) or ambient air (by means of a cooling fan). The heater can use solar energy concentrated by a solar collector or concentrator such as a Fresnel lens 7, as shown in Figure 1. The engine can be heated using other heat sources, e.g. geothermal energy, waste heat, or heat of combustion, or a combination of several heat sources. A diaphragm barrier unit 8 plays a role of an interface between the working fluid and a liquid to be pumped (shown in light green). All the installation is filled with a working fluid - carbon dioxide, water, hydrocarbons, refrigerants etc. depending on temperature of the available heat source.

When the displacer 2 moves down it displaces the liquid working fluid from the cold lower part through the cooler 4, regenerator 5 to the heater 6. The liquid heats up and turns into vapors, the pressure inside the cylinder rises and pushes out the liquid from the cold part of the cylinder to the diaphragm unit 8. The diaphragm transmits pressure to the liquid to be pumped displacing it through the upper (discharge) valve 9.

When the displacer moves up it displaces the hot vapors from the heater to the regenerator and the cooler back to the cold part. Vapors turn back into liquid and pressure in the cylinder drops down. At certain moment pressure becomes so low that the liquid working fluid is sucked from the diaphragm unit 8 back into the cylinder. The diaphragm unit, in turn, sucks the liquid to be pumped through the lower check valve 9. Figure 2 illustrates schematically the pressure change in the engine.

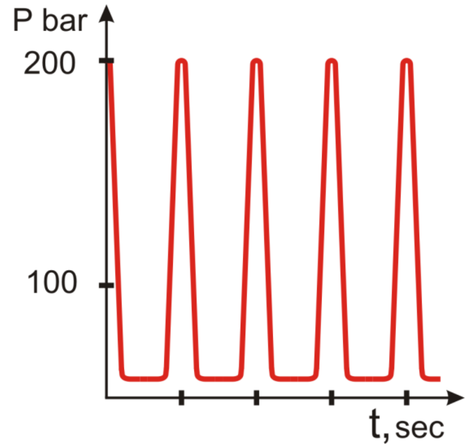

Figure 2. Pressure change in the engine.

In theory, if the regenerator is designed properly, efficiency of the converter can be very high, approaching Carnot efficiency.

The engine principle outlined above was implemented by Bush [5], Martini [6] and others using gas as working fluid.

In the final design the crank gear mechanism shown in Figure 1 can be eliminated. The displacer can be driven by many different ways e.g. by using energy of the compressed working fluid. A part of this energy can also be used to supply electricity, if necessary, to a control equipment (pressure/temperature sensors, controller etc). Without external driving mechanism and after addition of two sliding valves the engine becomes similar to the hot-air engine proposed by Manson [7, 8].

The recuperation of the energy of high pressure reject stream (brine) can be performed by a water hydraulic motor to produce electricity as in conventional RO processes. However this is not necessary because the pump proposed offers an opportunity to substantially improve the RO process. One of the most advantageous ways to use the pump for filtration processes is a cyclic flow operation shown in Figure 3. In this case a membrane RO unit 10 and an on/off valve 11 located on a reject stream line are combined with the heat driven pump outlined above.

In operation the valve 11 is open during the initial period of the displacer down stroke when the pressure in the engine is relatively low. At this stage the pump pushes out the feed saline water through the upper check valve 9 and RO unit to the reject stream line displacing the concentrate out of the membrane unit 10 and filling the membrane unit with feed saline water. Then the valve 11 closes. A subsequent movement of the displacer 2 down results in a build-up of the pressure in all installation. When the pressure exceed the osmotic pressure, the feed saline water is forced to flow through the membrane producing permeate. The pressure rises together with the concentration of salt in the brine maintaining the flow through the membrane.

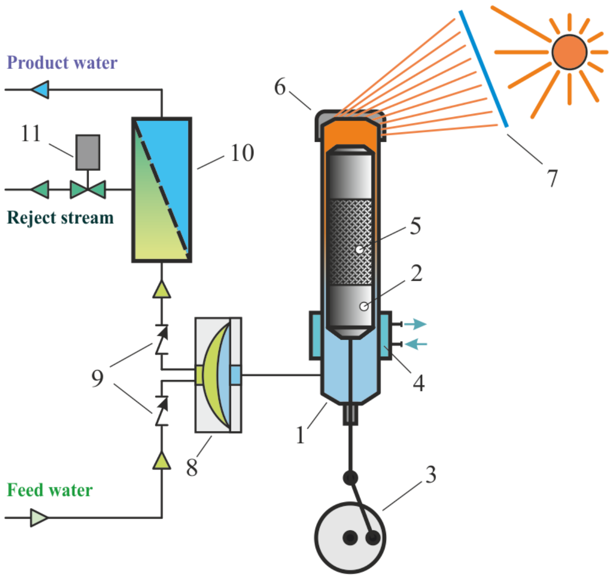

Figure 3. Basic principle of energy recuperation.

When the displacer moves up the pressure in the pump drops down. The diaphragm unit 8 sucks the feed water through the lower check valve 9. At certain pressure some part of the product water can flow through the membrane back to the brine, providing backwashing the membrane to avoid its fouling.

Such a scheme could be the simplest and energy efficient as no high-pressure reject stream is produced and accordingly no recuperation of the energy is required.

This technology provides high adjustable recovery rates, independently adjustable cross-flow and resistance to the flow through membrane and even flow reversal to prevent fouling and scaling.

2.2 Preliminary work and results

Several engines were designed, constructed and tested using water as working fluid. Technical feasibility of the novel concept was demonstrated and very promising results were obtained [9]. At temperature of the heater of 300 – 500 ^{0}C and temperature of the cooler of 30 – 40 ^{0}C the engine thermal efficiency was in the range of 5 – 10 %. The frequency of the displacer was 0.5 - 2 Hz. The relatively low efficiency is explained by poor regeneration due to the thermodynamic restrictions. Higher efficiency is expected at other operating conditions or with other working fluids enabling better heat regeneration. Increasing of the average pressure in the engine should lead to approximately proportional increase of the engine power and substantial improvement of the efficiency due to the expected increase in the regeneration capabilities.

The engines studied can be compared with conventional Stirling engines. The power parameter (the ratio of the power and the product of maximum pressure and total swept volume in compression and expansion spaces) for practical Stirling engines at the ratio of the temperatures in the compression and expansion spaces of 0.5 is not higher than 0.03 – 0.06 [10]. According to the measurements the power parameter is 0.23 or 4 – 8 times higher.

Real advantages of the tested engines can be seen in the values of operating temperatures and pressures. Heat source temperature of 300 ^{0}C was sufficient to run the engines with water. With working fluids used in ORC engines much lower temperatures are foreseen.

There is a very big difference in the pressures. In Stirling engines the ratio of the maximum and minimum pressures rarely exceeds 2 [10] whereas in the experiments performed it was as high as 5 – 50.

3 KEY FEATURES AND ADVANTAGES

The engine/pump performs a very unusual thermodynamic cycle with phase-change or supercritical working fluids such as CO_2. Numerous advantages of using CO_2 in power cycles were established long ago. Supercritical CO_2 offers a very high cycle efficiency in a compact footprint and a very broad range of heat sources temperatures. It is non-toxic, cheap and abundant. However sealing problems, design of compressor and turbo expander for supercritical CO_2 happened to be a very serious, non-trivial challenge, preventing the development and deployment such power plants [11]. The engine developed is based on alternative principles and allows for using CO_2. The compressor as such is missing at all; the cyclic process permits combining the compression with heating. The turbo expander is also eliminated, being replaced with the simplest piston unit operated with cold, liquid, non-supercritical CO_2.

The use of a dense working fluid permit generating very high pressures in one step – up to several hundred bars in contrary to well-known types of heat driven pumps. Due to the high pressure, the engine operating at rather low frequency of the displacer reciprocation of about 1 Hz, can provide the same energy density as state-of-the-art piston engines.

Converting heat directly to pressure of liquid makes the technology eminently suitable for pumping of water in various known water treatment processes and promises a substantial improvement of their economics. Since the pumps can generate very high pressures (hundreds bars) they can be used instead of modern plunger pumps driven by electric motors, thus eliminating completely the consumption of electricity for RO water desalination processes. Instead of the use of positive displacement (plunger) pumps the pumped fluids (water) are compressed directly by heat in the heat driven pumps (or compressors).

The engine proposed has a number of advantages compared to conventional prime movers.

A distinguishable feature of the engine/pump proposed is its simplicity resulting in increased lifetime and low cost. It does not have any high precision parts and even does not require expensive heat resistant high alloyed steels and any other expensive materials. The engine does not have typical technical problems of well-known heat engines: sealing, lubrication and wear. In view of the simplicity and decreased friction a realistic target maintenance interval is 50.000 hours. An estimated cost of a several kW engine in mass production is about a few hundred US dollars.

No high temperature heat sources are needed. The technology can be economical even at a very low temperature of heat source. The pump can be powered by any source of heat with temperature from 60 ^{0}C to 1000 ^{0}C. Heat sources with temperature of 200 – 300 ^{0}C could be sufficient to create pressure drops typical of RO processes. Therefore different sustainable and renewable energy sources such as solar radiation, waste heat, and geothermal energy can be used to power the pump. Replacement of fossil fuels with renewable energy sources in desalination processes will minimize greenhouse gas emissions. The use of solar radiation as the energy input in desalination processes is one of the most promising applications of the renewable energies.

The hydraulic power output offers great flexibility to the process. An advantage of the hydraulic output is that it permits converting heat directly to pressure of liquid to be pumped i.e. allows direct driving of piston and diaphragm pumps and compressors. As a result new desalination processes could be proposed. The flexibility of the hydraulic power output permits to eliminate the problems with energy recuperation in RO processes: the pump itself may function as energy recovery devise.

Any desalination plant uses many water pumps. With the technology proposed all the pumps can be driven by the same hydraulics power source. Moreover, the hydraulic output gives a possibility to transmit power on long distance from multiple engines, etc.

The power can easily be increased by using a number of the engines in parallel serving one hydraulic line. The efficiency can be improved by the use of a cascade of engine-pumps operating at different temperature levels. Thermal energy storage, in case of solar collectors, can be an additional source of higher energy efficiency. This makes the technology eminently suitable for water treatment applications e.g. for pumping of water in various known water desalination processes. Compared to conventional gas Stirling engines the pressure amplitude generated by the engines is much larger (100-300 bar) and sufficient for any pressure-driven membrane technologies.

Pressure-driven membrane technologies for water treatment include not only RO, but also nanofiltration, ultrafiltration and microfiltration. These pressure-driven technologies could also profit from the application of heat powered pumps proposed.

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