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Heat pumps as a source of heat energy for desalination of seawater

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Abstract

Thermal desalination plants consume large quantities of heat energy for seawater evaporation. In condensing water vapor procured in evaporators and cooling distillate, a major part of heat energy is lost in the environment. Heat energy in processes of condensation and evaporation in desalination of seawater is quantitatively equal but these processes take place under different temperatures. Different power plants such as turbines of thermal and atomic power stations usually are the source of heat energy for the desalination process. Extraction of heat for evaporators for desalters reduces heat and electric power production of power plants. Besides emission of heat, energy from desalters in the environment results in its heat pollution, a greenhouse effect. Thermodynamic analysis described in this paper shows that the heat pumps make it possible to use heat energy effectively at desalination plants. It is provided with the incorporation of a heat pump in the flow diagram of the desalination plant.

Keywords: Heat pump; Thermal desalination plant; Seawater; Desalination

1. Introduction

Production of fresh water from seawater increases in the world by 5–7% annually. Seawater is processed into sweet water in large desalination plants, most often of thermal desalination. Thermal desalination plants require

a large quantity of heat energy. Thermal desalters operate in cyclic process. This process, by its physical character, is close to the power cycle of a steam power plant (Rankine cycle) and is coincidental to the thermodynamic cycle of the heat pump with regard to its reversibility. Consequently efficiency in the operation of

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powerful desalination plants increases greatly by incorporation of heat pumps for example of absorption type in the diagram of thermal desalination plants [1].

In addition to powerful desalination plants [2,3], manufacturers and consumers show great interest in small capacity desalters to obtain fresh water for industrial and domestic purposes. In many countries there are coastal areas where the quantity of natural drinking water is limited. In most cases day water production requires expensive purification systems which are not ecologically safe. Production of underground water is difficult or dead weight of artesian wells is insufficient. Therefore seacoast populations have to resort to desalination.

In that case desalters with the capacity of 5–100 tons of fresh water per day are used. Membrane methods of desalination are more often used in such plants. Membrane plants often consume only electric power for desalination. The main disadvantages of membrane desalters are the high cost of the product, insufficient reliability of operation and instability in control over the set parameters for quality of the desalted water. That is why it is necessary to control and maintain equipment that is often unacceptable for small desalination plants.

The use of thermal desalters with electric boilers may be considered as an acceptable solution to maintain domestic water supply, but such plants are economically sound only in countries with a cold climate. In that case they may be used as heating systems at the same time.

Thus a source of heat consuming little electric power and operating without heat loss is required for a highly efficient and reliable operation of thermal desalination plant. A heat pump may become such a source of heat. The heat pump not only allows reduction of consumption of expensive electric power, but also recovers all waste heat as well as using natural sources of heat for desalination: heat energy of sea water, air and solar energy [4,5].

Heat pumps operating on a reverse thermodynamic cycle may be used for a number of purposes simultaneously, firstly, as heating plants in the northern countries, secondly, as air-conditioners in southern countries and finally, as a source of heat for desalination in both cases.

2. Discussion

In industrially developed countries there are three main types of heat pumps: compression, absorption and ejector heat pumps which are widely used for heating and hot water supply. Compression heat pumps have the simplest design, but their use depends on reliable and effective high-pressure compressors. Absorption heat pumps are closer in principle to the operation of the well-known power plants, as their flow diagram incorporates traditional configuration of power equipment. The principle of compression for ejector heat pumps is widely used for waste-heat recovery in industry and heat power stations.

Each type of heat pump has its advantages and disadvantages. Thus it is necessary to make preliminary thermodynamic, technical and economic calculations when choosing the type to be used.

Absorption heat pumps can be used in high-capacity desalination plants. Ejector heat pumps are less effective. Using compression heat pumps in that case is not expedient as their unit capacity is significantly limited [1].

It is most expedient to use compression heat pumps for small-capacity desalination plants as they consume electric or mechanical energy for its motor. The use of absorption or ejector heat pumps is possible only on availability of an electric steam generator in the heat pump design. Besides, the technological structure of absorption and ejector heat pumps is more difficult than the structure of compression heat pumps.

A basic diagram of a compression heat pump operating in conjunction with thermal flashing (adiabatic) desalters is shown in Fig. 1.

The following processes take place in the plant. The seawater is fed through pump 1 into closed heater 2 where its temperature increases up to the required level. In multistage evaporator (3,4,5) at the cost of reduction of pressure of heated water, it boils up. The vapor obtained from the seawater at each stage condenses on film coolers 6, collects at storage units 7 and allocates to distillate tank 8. Brine from the last stage of desalination plant is fed to regenerative heat exchanger 9 for more significant cooling before sea burial. Source of heat for desalination process is vapor of agent R12, ammonia (or other substances with low vaporization temperature) being obtained behind compressor of heat pump 10. This vapor R12 having high pressure and temperature is a heating medium in heat exchanger 2. Then vapor after reducing pressure and temperature in reducers, goes through in sequence coolers at each stage of desalination

plant. The operating cycle of compression heat pump is over when at the last stage vapor R12 is heated up in regenerative heat exchangers and again directed to the compressor of heat pump 10.

In the operation of the desalination plants with the compression heat pump given, the temperature of brine at discharge may be equal and even below the temperature of the seawater intake. In that case energy in desalination plants is used only for the motor of compressor and pump as well as for compensation of heat losses of inconvertibility of thermodynamic processes: expansion, heat transfer etc. In desalination plants useful heat is used to obtain water vapor from which distillate is derived. Thus available heat factor $\varphi_d = Q_d/L_c$ can be used as a ratio showing efficiency of the whole plant operation where Q_d is a quantity of heat used from compression heat pump in the process of obtaining distillate; L_c is an energy expended for the motor of compressor and pump. Cyclic processes of the compression heat pump which maintains the operation of three-stage thermal desalination plants are

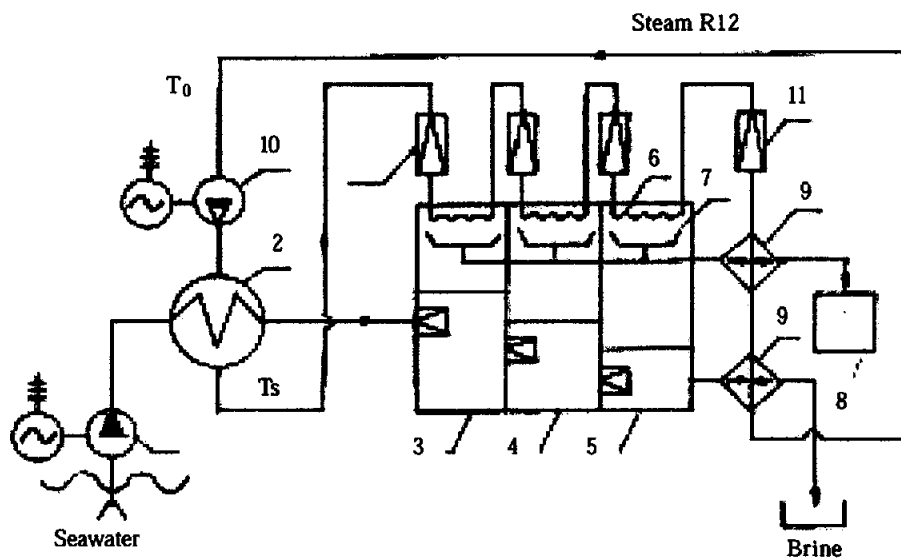


Fig. 1. Diagram of a desalination plant with compression heat pump, cycle at R12; 1, pump; 2, heat pump condenser; 3, 4, 5, stages of evaporator; 6, cooler; 7, distillate storage unit; 8, tank for distillate discharge; 9, regenerative heat exchanger; 10, heat pump compressor; 11, reducer.

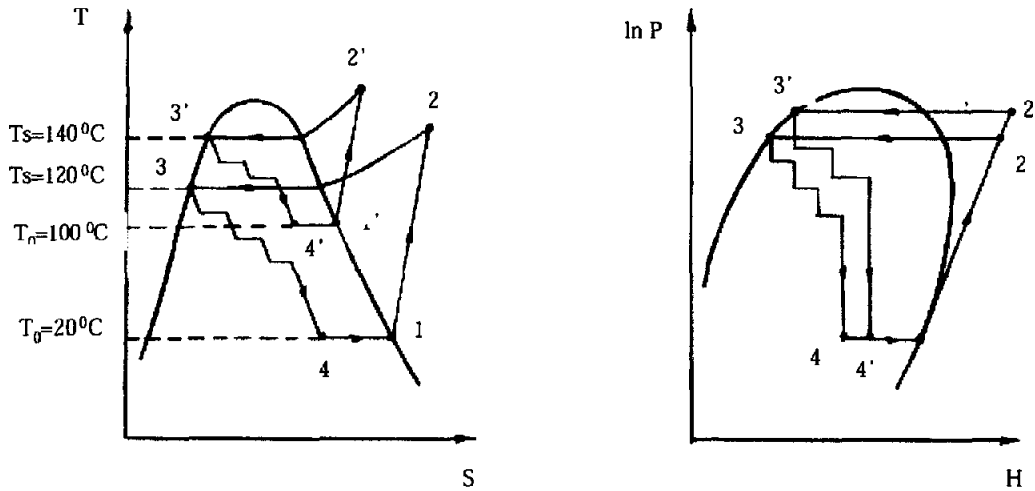


Fig. 2. Compression heat pump cycle in thermodynamic diagrams; 1, 2, 3, 4, compression heat pump cycle at R12; 1',2',3',4', steam and water compression heat pump cycle.

illustrated in Fig. 2 in T-S and P-H thermodynamic diagrams. Compression heat pump cycle consists of process vapor compression in compressor 1, 2, condensation process 2, 3, processes of throttling and heat supply in three stages of desalination plants and regenerative heat exchangers 3, 4, 1.

Taking into account that pump 1 substantially consumes a smaller part of energy in comparison with compressor 10 we have:

$$\varphi_d = (H_2 - H_3) / (H_2 - H_1) \tag{1}$$

where H_1, H_2, H_3 are enthalpy R12 before and after compressor and behind condenser of compression heat pump.

A value $m = G_s / G_c$, ratio between mass flows of water vapor and agent R12, is of great importance to thermodynamic calculations. Without considering heat losses, m obtained from equation of heat balance of the heat exchanger 2, Fig.1:

$$m = (H_2 - H_3) / C_s (T_s - T_0) \tag{2}$$

where C_s is heat capacity of water.

Thermodynamic efficiency of the heat pump cycle is usually estimated by value of heat transformation ratio φ_t . Maximum value of φ_t can be determined in accordance with the Carnot theorem:

$$\varphi_t = T_s / (T_s - T_0) \tag{3}$$

where T_s and T_0 are maximum and minimum mean integral temperatures of heat pump cycle. Taking the value of seawater temperature T_0 from 0–20°C and limiting the temperature range of operation of evaporating stage of the desalination plant $60^\circ\text{C} < T_s < 260^\circ\text{C}$ it is possible to calculate ratios φ_d and φ_t , Fig.3.

Solving Eqs. (2) and (3) simultaneously we get:

$$m = \varphi_t \cdot (H_2 - H_3) / H_s^* \tag{4}$$

where H_s^* is enthalpy of water condensation at temperature T_s .

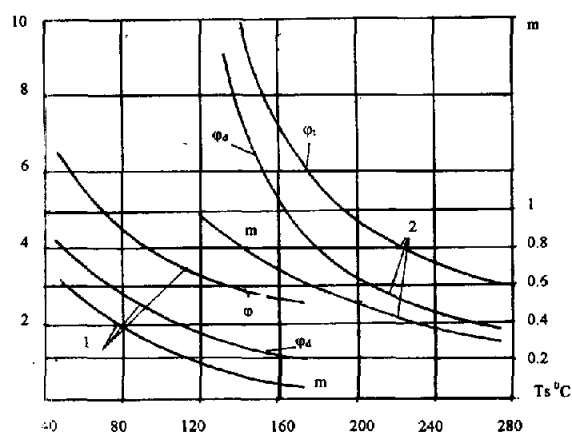


Fig. 3. Thermodynamic values of the desalination plant with compression heat pump; 1, for compression heat pump cycle with R12; 2, for steam and water cycle of compression heat pump.

From Eqs. (1) and (4) it is possible to find a relation between ratios affecting thermodynamic efficiency and specific capacity m of the desalination plant with compression heat pump:

$$m = \varphi_1 \cdot \varphi_d (H_2 - H_1) / H_s^* \quad (5)$$

Thus relative capacity of the desalination plant depends on the value of the heat transformation ratio in compression heat pump and available heat factor as well as on the kind of working medium used in the compression heat pump.

The main disadvantages of compression heat pump with working medium R12 or other agents used in refrigerating engineering, are impossibility to reach high temperatures behind compressor (T_s not more than 120–160°C at $T_o = 0^\circ\text{C}$) in connection with thermal instability of such substances. That is why values of ratios m , φ_1 , φ_d at $T_s > 100^\circ\text{C}$ are not big. At lower T_s it is necessary to use vacuum adiabatic evaporators which substantially complicates desalination plant construction.

An acceptable technical solution in that case would be application of the compression heat pump with use of water vapor as a working medium. A diagram of a desalination plant with steam and water cycle of compression heat pump is given in Fig. 4 (units shown are the same as in Fig. 1). In this diagram the plant operates at higher temperatures of seawater evaporation $T_s > 100^\circ\text{C}$, $T_o = 100^\circ\text{C}$ which allows substantial

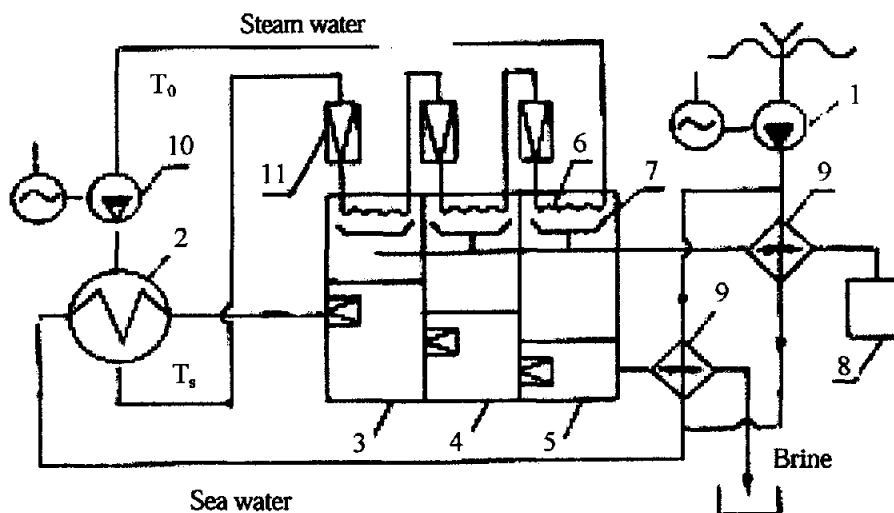


Fig. 4. Diagram of desalination plant with compression heat pump in steam and water cycle.

increase of thermodynamic efficiency of the operation of equipment, Fig. 3.

In determining variations of m for the 2nd diagram the following relation is used:

$$m = (H_2 - H_3)/(H_1 - H_3) \quad (6)$$

where enthalpies of steam and water cycle of heat pump H_2 and H_3 depend on temperature T_s and H_1 depends on T_0 .

The principle of operation and diagram of desalters equipped with compression heat pumps is considerably different from characteristics of well-known compression desalination plants. In compression desalters manufactured by the firms Bager (USA), Richardson (England), Astra (Germany) and others, the compressor is designed to increase pressure and temperature of vapor taken from the last stage of desalination plants. Such plants operate not on closed, but open thermodynamic cycle. It is necessary to maintain deep regeneration of heat from brine, distillate from the first evaporating stages as well as distillate from the main heat exchanger. This complicates the structure of the desalination plant and increases irreversible heat losses. Besides heat transformation the ratio in open cycle diagrams is almost half as much as in diagrams with compression heat pump.

Thus desalination plants integrated with compression heat pumps along with steam compression desalination plants now can be considered to produce distillate from seawater. They can maintain water supply of high quality for small fixed and mobile consumers of fresh water.

3. Conclusions

- In the constant increase in fresh water demand it is necessary to manufacture simple

in operation, reliable and cost-effective desalination plants with the capacity of 5–100 tons of fresh water per day for industrial and domestic purposes which operate on electric power. Membrane and thermal desalters have such properties.

- The structure of the effective thermal desalination small-capacity plant should incorporate a heat pump for waste heat recovery and reduced power consumption to produce fresh water. Such devices are compression heat pumps.
- To manufacture desalters integrated with compression heat pumps it is possible to use additional energy as natural heat from seawater, as well as to maintain heating, hot water supply and air-conditioning of the buildings.
- Connection of a thermal desalination plant to a compression heat pump operating on steam and water cycle increases by 2–3 times the economical and thermodynamic indicators of the desalination process. It allows for the substantial reduction of the cost of production of desalinated water.

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