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ORGANIC RANKINE CYCLE WITH SOLAR HEAT STORAGE IN PARAFFIN WAX

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Abstract

The paper presents an electricity generation system based on an Organic Rankine Cycle and proposed storing the amount of the heat produced by the solar panels using large volume of paraffin wax. The proposed working fluid is R-134a refrigerant. The cycle operates at very low temperatures. A efficiency of 6,55% was obtained.

Key words: solar heat storage, phase change material, Organic Rankine Cycle

1. Introduction

Solar energy is one of the most important renewable energy resources. The most common applications currently used to convert solar energy in residential and tertiary sectors are solar panels and photovoltaic panels.

In periods with intense solar radiation, the heat produced by the solar panels is often greater than the needs of the users.

In the paper is proposed storing the amount of the heat produced by the solar panels during periods in which there is no hot water consumption and using stored thermal energy to produce electricity. The heat storage medium is a phase change material. It is presented and analyzed an electricity generation system based on an Organic Rankine Cycle.

Unlike the classical Rankine cycle, using water as working fluid, the Organic Rankine Cycle working agent is a fluid with lower vaporization temperature. The advantage is that the Organic Rankine Cycle allows plants capable of producing electricity using low temperature heat sources [1]. Organic Rankine Cycle can also be used as bottoming cycle in combined cycles for producing energy [2].

In Organic Rankine Cycles the enthalpy drop is much lower and single stage turbines with small dimensions are usually used, leads to a low cost of the system [3].

2. Selection of the phase change material

A phase change material is a substance with a high latent heat, which through melting and solidifying, at a certain temperature, is able to store and release large quantities of heat [4]. Water output temperature from the solar panels is usually between 70-80°C. Phase change material to be used for the storage of solar heat must have a phase change temperature below 70°C. From the list of phase change materials currently available [5], most appropriate for this level of temperature is the paraffin wax.

The paraffin wax is in class paraffin, saturated hydrocarbons, with molecular structure type C_mH_{2n+2}. Paraffin wax is obtained from petroleum distillation process and is not a pure substance, it is generally a combination of various hydrocarbons [6]. The main thermophysical properties of paraffin wax, table 1, are presented in literature [7].

Table 1: Thermophysical properties of paraffin wax

Property	**Unit**	**Value**
Melting range	K	316-329
Density	Kg/m^3	900-970
Specific heat	kJ/kg K	2,0-2,9
Heat of fusion	kJ/kg	190-210
Thermal conductivity	W/m K	0.22-0,24

Paraffin wax is a non-reactive and safe storage medium, compatible with all metal containers and easily incorporated into heat storage systems [8].

Unlike other applications in which paraffin wax is inside capsules [9] or tubes [10], [11], this paper proposes heat storage in a large volume of paraffin wax.

The studies have shown that paraffin wax have stable properties after 1000-2000 cycles. The thermal properties of the paraffin wax have not change after repeated melting/solidification cycles [12].

3. The proposed Organic Rankine Cycle power plant

The proposed ORC power plant is presented in fig. 1. Heat contained in hot water produced by the solar panels 1 is stored in the paraffin wax through heat exchanger 3. Pump 2 performs water circulation in solar panels 1 and heat exchanger 3. The volume of the thermal accumulator 4, where is stored the paraffin wax, must be large enough to allow the storage of larger amounts of heat. When paraffin wax is in liquid phase, the stored heat is transferred to the working fluid of the cycle in the heat exchanger 5. In this heat exchanger the working fluid is heated and vaporized. The heat exchanger design must ensure an optimal heat flow between paraffin wax and the working fluid [13]. Vapors are expanded in the turbine 6 and condensed in the condenser 8. The turbine drives electrical generator 7. Pump 9 increases the condensate pressure to the vaporization pressure.

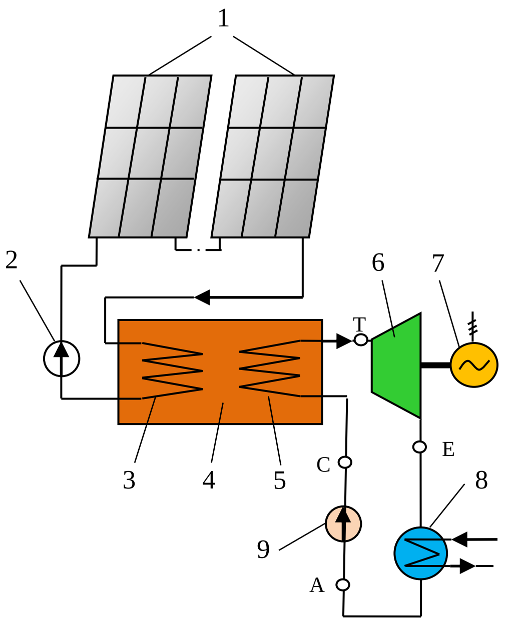

Fig. 1: Organic Rankine Cycle power plant

The working fluid must have the necessary thermo-physical properties for this application but also it is necessary to have adequate chemical stability in the temperature range [14]. The working fluid should be noncorrosive and compatible with materials of the power plant components..

The chosen working fluid is R-134a refrigerant, 1,1,1,2-Tetrafluoroethane, chemical formula CH_2FCF_3. This is a nontoxic and nonflammable fluid. Its ozone depletion potential is zero and the global warming potential is 1300. The critical temperature and critical pressure are 101,1ºC and 40,6 bar [15]. R-134a properties make it suitable for use in Organic Rankine Cycles with very low temperature sources.

The slope of saturation curve for R-134a shows that this working fluid has almost isentropic expansion in the turbine.

The thermodynamic cycle, using enthalpy-entropy (h-s) axis, is represented in fig. 2. The main points of the cycle are also represented in fig. 1.

Considering the melting point of wax paraffin 56-60°C, the R-134a maximum temperature of 50°C was adopted. Point T is on the saturation curve. The saturation pressure of R-134a at 50°C is 13,179 bar. This is the maximum pressure in the cycle.

The minimum temperature of the cycle is in condensing process (between points E and A). This temperature was adopted 22°C, in order to achieve cooling of the condenser. A condensing pressure higher than atmospheric pressure prevents air infiltration in the cycle. The minimum pressure of the cycle is 6,078 bar, which is the saturation pressure at the temperature of 22°C.

Thermodynamic properties of R-134a were determined according to [15].

Theoretical the expansion process in turbine is isentropic, between points T and E_0. The real expansion process, considering the energy losses of the turbine, is between point T and point E. A turbine efficiency of 0,8 was considered. The real expansion process overlaps saturation curve. The points E and A are located on the saturation curve: $x_E = 1$, $x_A = 0$, where x is the title of the vapors.

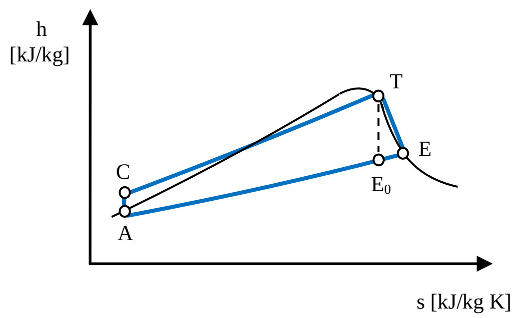

Fig. 2: Thermodynamic cycle

Vaporization and condensation processes are considered isobaric.

Superheating of the vapors before entering the turbine would lead to increasing the amount of waste heat from the condenser and would not contribute to increasing the efficiency of the cycle. When the point E is on the saturation curve, waste heat from condenser will be minimal.

The R-134a parameters in the main point of the cycle are presented in table 2.

Table 2: Parameters in the main points of the cycle

	A	**T**	**E_0**	**E**
p[bar]	6,078	13,179	6,078	6,078
t [ºC]	22,00	50,00	22,00	22,00
h [kJ/kg]	230,29	423,44	407,63	410,79
s [kJ/kg K]	1,1057	1,7072	1,7072	1,7173
x	0	1	0.983	1

The high value of the title of vapors in the point E_0 shows that the expansion process is nearly isentropic.

4. Cycle efficiency and power calculation

Based on the parameters presented in table 2, the turbine power and the efficiency of the cycle can be calculated.

The specific energy e_t developed in the turbine for 1 kg R-134a mass flow is the difference between the enthalpy of the working fluid inlet (h_T) and outlet (h_E) of the turbine:

$$e_t = h_T - h_E \quad [kJ/kg] \tag{1}$$

The value of the specific energy is e_t = 12,65 [kJ/kg].

The thermal efficiency η_t of the proposed Organic Rankine Cycle is:

$$\eta_t = \frac{h_T - h_E}{h_T - h_A} \tag{2}$$

where h_T-h_A represents the input energy of the cycle.

The value of thermal efficiency is η_t = 6,55 %. The efficiency of the Carnot Cycle in the same temperature range is 8,72 %.

The power of the turbine can be calculated with relation:

$$P_t = G \cdot e_t \quad [kW] \tag{3}$$

where G represents the R-134a mass flow [kg/s] .

Dependence between the power turbine and the mass flow is linear.

The useful energy of the cycle is the difference between the energy produced by the turbine and energy consumption for increased pressure of working fluid in the pump.

$$e_u = e_T - (h_C - h_A) \quad [kJ/kg] \tag{4}$$

Literature shows that, for a low temperature Organic Rankine Cycle using R-134a, pump energy consumption is usually 10% of the turbine power. [3].

The useful power P_u represents power available at the turbine shaft:

$$P_u = G \cdot e_u \quad [kW] \tag{5}$$

The electric power of generator P_e is calculated using the relation:

$$P_e = P_u \cdot \eta_{eg} \quad [kW] \tag{6}$$

η_{eg} represents the efficiency of the electric generator. In the table 3 are presented the values of turbine power and electric generator power for different values of the R-134a mass flow. It was considered a pump consumption by 10% of the turbine power and the efficiency of electric generator η_{eg} = 0,94.

Table 3: Turbine power and electric power

G [kg/s]	P_t [kW]	P_e [kW]
0,10	1.265	1.070
0,15	1.897	1.605
0,20	2.530	2.140
0,25	3.162	2.675
0,30	3.795	3.210
0,35	4.427	3.745
0,40	5.060	4.280

5. Conclusions

The proposed energy system is able to provide a part of the electricity demand of residential or tertiary sector users. The amount of electricity produced depends on the operating time of the small power plant. In the summer, the estimated time of operation is 4-5 hours/day. The produced energy is a “clean energy” and its production cost is zero.

The low value of the thermal efficiency is due to the small difference between maximum and minimum temperature in the cycle, which is 28°C. The thermal efficiency value is similar to those presented in the literature, for the Organic Rankine Cycles with heat recovery from low-temperature sources [16], [17].

Turbine power and electric generator power are in linear dependence to the working fluid mass flow.

Increasing R-134a mass flow in order to obtain a higher power involve large dimensions of the thermal accumulator, a considerable amount of paraffin wax and a large number of solar panels. For residential users or tertiary sector users the mass flow values presented in table 3 ensure optimum size of power plant.

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