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ANALYSIS OF WORKING FLUIDS FOR AN ORGANIC RANKINE CYCLE WITH RECOVERY OF HEAT STORED IN PARAFFIN WAX

BY

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Abstract. The paper presents a comparative analysis on the efficiency of an organic Rankine cycle, operating at a very low temperature, considering three working fluids: R134a, R22, R600a. The necessary vaporization heat of the working fluid is provided by heat stored in paraffin wax. The values of the energy produced in cycle and of the cycle efficiency are compared.

Key words: organic Rankine cycle; heat storage; efficiency.

1. Introduction

The energy systems that use renewable energy resources at a low thermal potential usually works on the principle of organic Rankine cycle. The organic Rankine cycle (ORC) applies the same principle like the classical steam Rankine cycle, difference is that the working agent is an organic fluid with low

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boiling points (Chen *et al.*, 2010). The organic Rankine cycle is able to to recover heat from lower temperature sources (Tchanche *et al.*, 2011).

Using energy sources with low temperature involved often energy storage because heat supply is discontinuous (Dincer & Rosen, 2010). Among the methods of thermal energy storage, latent heat storage (LHS) provide smaller volume of the storage system (Zalba *et al.*, 2003). Materials used in latent heat storage process are called phase change materials (PCM). A phase change material is a substance with a high latent heat, which through melting and solidifying, is able to store and release large quantities of heat (Om Nayak *et al.*, 2011). From the list of phase change materials currently available, most appropriate for a very low level of temperature is the paraffin wax.

The paper studying the possibility of producing electricity using ORC cycle, which run on heat stored in paraffin wax at a very low level of temperature. As working agent for the organic Rankine cycle are analyzed following fluids: R134a - tetraflouroethane, R22 - chlorodifluoromethane, R600a - isobutene. These three organic fluids have low global warming potential and ozone depletion potential. Analysis is done considering theoretical cycles.

2. Thermodynamic Cycles and ORC System

Because the melting point of paraffine wax is in range 55°C - 60°C, a maximum temperature of 50°C for the organic fluid vapor was adopted (point T). The minimum temperature of the cycle was adopted 22°C, in order to achieve cooling of the condenser.

Saturation curve shape is similar for R134a and R22. The thermodynamic cycle for these two fluids is represented, using enthalpy-entropy axis, in Fig. 1. The thermodynamic processes of the cycle are: AC – increase of the pressure; CT – isobaric heating and vaporization; TE_0 – theoretical expansion; TE – real expansion; EA – isobaric condensation.

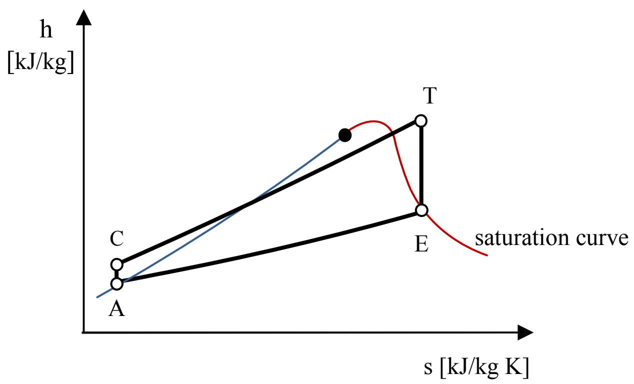

Fig. 1 – The h-s diagram of the organic Rankine cycle (R 134a, R22).

To minimize heat losses to the condenser, point E is considered on the saturation curve. Condenser pressure is the saturation pressure of R134a and R22, corresponding to temperature of 22°C. In point T fluids are slightly superheated. The slope of saturation curve of R600a is different from the first two fluids. In order to compare the energy produced by expansion and the efficiency of the cycles, maximum and minimum temperature in the cycle are the same. In point T temperature is also adopted 50°C, but in this case point T is on the saturation curve. The temperature in point E is also 22°C, but the point E is in the superheated vapour domain. The pressure in point T is the saturation pressure corresponding to the temperature of 50°C of R600a for each working fluid. Pressure in point E is saturation pressure of R600a for a temperature of 22°C. The thermodynamic cycle for R600a is represented in Fig. 2.

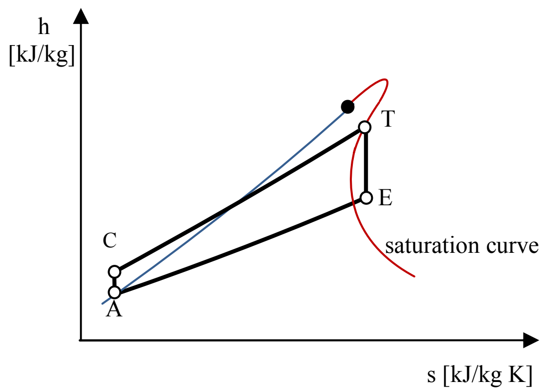

Fig. 2 – The h-s diagram of the organic Rankine cycle -R600a.

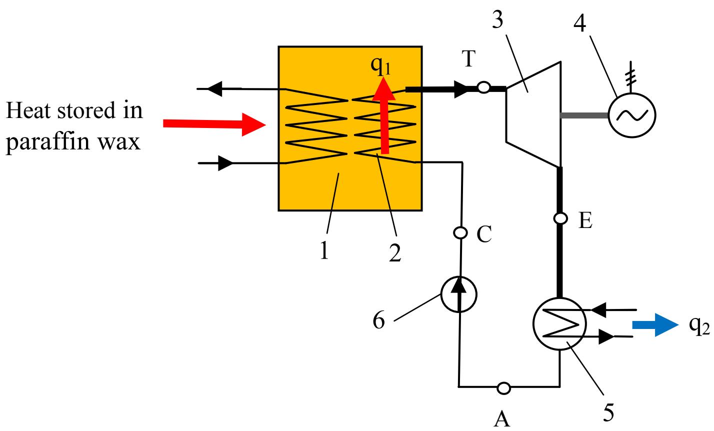

Fig. 3 – The ORC system:
1 – paraffin wax tank; 2 – vaporiser; 3 – turbine;
4 – electric generator; 5 – condenser; 6 – pump.

The ORC power system is presented in Fig. 3. Working fluid vaporization heat required is provided by heat stored in paraffin wax.

To retrieve the amount of heat required for vaporization of the working fluid, the surface vaporiser must be sufficiently large. This heat exchanger must have a proper geometry and heat exchange area must be evenly distributed throughout the volume of paraffin wax (Luca *et al.*, 2015).

Condenser cooling can be done with water or air.

3. Results and Discussions

In order to calculate cycle efficiency, parameters in the main points of the cycle, for each working fluid, were determined. Thermodynamic properties of the three organic fluids were adopted according to (ASHRAE Handbook Fundamentals, 2009).

The parameters in the main points for each of the organic fluid are presented in Table 1.

Table 1
Working Fluids Parameters in the Main Point of the Cycle

Point	Parameter	R134a	R22	R600a
A	p, [bar]	6.078	9.619	3.232
	t, [ºC]	22.00	22.00	22.00
	h, [kJ/kg]	230.29	225.56	251.07
T	p, [bar]	13.179	16.013	6.919
	t, [ºC]	50.00	50.00	50.00
	h, [kJ/kg]	423.44	424.82	623.17
E	p, [bar]	6.078	9.619	3.232
	t, [ºC]	22.00	22.00	26.35
	h, [kJ/kg]	410.79	412.49	593.18

The thermal efficiency η_t of the organic Rankine cycle is calculated using eq. (1):

$$\eta_t = \frac{h_T - h_E}{h_T - h_A}. \quad (1)$$

where: $h_T - h_A$ represents the input specific energy of the cycle; $h_T - h_A$ is specific energy produced by the turbine.

The specific energy e_t developed in the turbine represents the difference between the enthalpy of the working fluid inlet (h_T) and outlet (h_E) of the turbine, eq. (2):

$$e_t = h_T - h_E \text{ , [kJ/kg]} \quad (2)$$

Another important parameter is the quantities of waste heat from the condenser for 1 kg mass flow of working fluid, q_2.

$$q_2 = h_E - h_A \text{ , [kJ/kg]} \quad (3)$$

A high value of q_2 indicate high energy consumption for cooling condenser.

Values of the energy developed by the turbine, cycle efficiency and the waste heat from the condenser are presented in Table 2.

Table 2

Turbine Energy, Efficiency, Heat from Condenser

Organic fluid	e_t [kJ/kg]	η_t [%]	q_2 [kJ/kg]
R134a	12.65	6.58	180.50
R22	12.33	6.18	186.93
R600a	29.99	8.05	342.11

The low value of the thermal efficiency is due to the small difference between maximum and minimum temperature in the cycle, which is 22°C. The thermal efficiency value is similar to those presented in the literature, for the ORC with heat recovery from low-temperature sources (Khennich & Galanis, 2012). The efficiency of the Carnot Cycle in the same temperature range is 8.72%.

The results for R134a and R22 a comparable. Although the energy produced by the turbine is approximately 230% higher for R600a, cycle efficiency is only 23% higher than R134. The waste heat from the condenser for R600a is almost double than R134 and R22, which causes a higher energy consumption for cooling the condenser.

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ANALIZA FLUIDELOR DE LUCRU PENTRU UN CICLU RANKINE ORGANIC CU RECUPERAREA CĂLDURII STOCATE ÎN CEARA PARAFINICĂ

(Rezumat)

Lucrarea prezintă o analiză comparativă asupra eficienței unui ciclu Rankine organic, luându-se în considerare trei fluide de lucru diferite: R134a, R22, R600a. Aportul de căldură în ciclu se face prin preluarea căldurii stocate într-un material cu schimbare de fază şi anume ceara parafinică. Sunt determinați parametrii în punctele principale ale ciclului termodinamic pentru cele trei fluide de lucru şi sunt calculate valorile energiei produse la turbină, eficienței termice şi căldurii evacuate la condensator.