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MODEL FOR THE BEHAVIOUR OF LOW TEMPERATURE AND SMALL SIZE ORC EQUIPMENT

BY

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Abstract. The study presents specific information about theory and operation of low temperature and small size ORC equipment, followed by the algorithm of thermal calculation of working cycle. The obtained global electric efficiency is of ≈8% in good agreement with the available literature. The most important result of the study is a model capable to calculate the thermal power needed to operate the ORC equipment, in function of the requested electric power and of the available temperature of the hot source.

Key words: ORC; electric efficiency; modelling; R245fa; working temperature.

1. Introduction

The conversion in electric energy of available heat from renewable energy sources or from different industrial processes is an efficient solution of efficient harvesting of different available forms of energy with very few options for other practical use.

If the available heat presents a sufficient high thermal potential from the temperature and thermal power points of view, a possible solution of conversion

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into electricity is the classic ***S***team ***R***ankine ***C***ycle (***SRC***) (Cengel & Boles, 2001; Moran, 1999; Mărădăşan & Bălan, 1999).

If the temperature level of the available renewable or residual heat is low, for the conversion in electricity it can be used a Rankine cycle with organic fluids as working agents. This cycle is named the ***O***rganic ***R***ankine ***C***ycle (***ORC***) and can be used for a very large range of provided electric power: low, medium or high (Beith, 2011).

In ***ORC*** equipment can be used as organic fluids: siloxanes (substances with chemical links Si-O-Si), hydrocarbons or refrigerants (Beith, 2011).

This study concerning the ***ORC*** equipment behaviour under different required electric power and variable available temperature was realised to analyse the ***ORC*** equipment capacity to adapt at different operation conditions. The study is important because in real operating situations, both electric power required by the consumer and temperature of the available heat source, are variable and it is important to know the limits of ***ORC*** equipment and its flexibility under these variable conditions.

The ***ORC*** equipment was considered of low temperature because the hot source temperature (t_h) was considered in the range of (80-120)°C, which is typical for solar and geothermal systems. The small size of ***ORC*** equipment is characterised by the small required electric power (P_{el}) considered in the range of (0.5-4.5) kW.

The goal of this study was to evaluate the dependence between the needed thermal power ($\dot{Q}_0$) function of the requested electric power of the ***ORC*** equipment (P_{el}) and of the available hot source temperature (t_h).

2. Material

The principle scheme of equipment operating by the ***ORC*** cycle, is presented in Fig. 1.

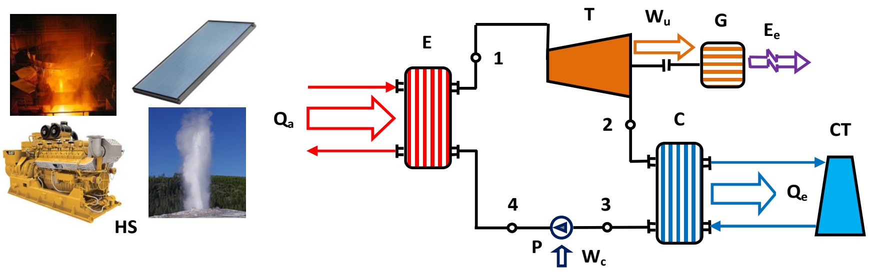


Fig. 1 – Principle scheme of equipment operating by the ***ORC*** cycle.
HS – Heat source; E – Evaporator; T – Turbine (or expander); G – Electric generator; C – Condenser; CT – Cooling tower; P – Pump; Q_a – Absorbed heat; W_u – Useful work; E_e – Electric energy; Q_e – Evacuated heat; W_c – Work of compression; 1 – High pressure vapours; 2 – Low pressure vapours; 3 – Low pressure liquid; 4 – High pressure liquid.

In the evaporator (E), the available heat from a renewable source or recovered from a technological process (Q_a) is absorbed by the working agent that evaporates at relative low temperature and pressure. The saturated or low superheated vapours (1) are expanding in the turbine or expander (T), where the useful mechanical work (W_u) is produced and is then converted in the electrical generator (G) into electric energy (E_e). Turbines are usually used in medium and high power equipment, while expanders are used in low power equipment. At the outlet of the turbine or expander are evacuated low pressure vapours (2). In the condenser (C), these vapours are condensing evacuating heat into the environment (Q_e) through the cooling agent of the condenser, which can be either water or air. In the case of water cooling condensers, water is evacuating the heat in the cooling tower (CT), where the heat extracted from the condenser is evacuated into the ambient air while the water is cooled down up to the wet bulb temperature. The liquid condensate at low pressure (3) is compressed by the pump (P) and its potential energy is increased by consuming the compression mechanical work (W_c). The evacuated high pressure liquid (4) is introduced in the evaporator (sometimes named vapours generator) and the cycle repeats.

The working cycle of ***ORC*** equipment is presented in the temperature – entropy (T-s) diagram in Fig. 2.

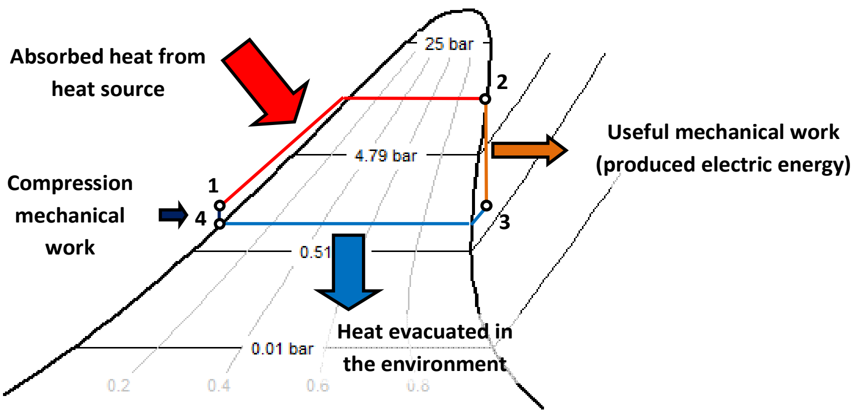


Fig. 2 − The working cycle of ***ORC*** equipment, in the T-s diagram.

The working agents from the ***ORC*** equipment present different thermal properties that are influencing both the working conditions (mainly pressures and temperatures) and the energy performances.

The main energy performances are the following:

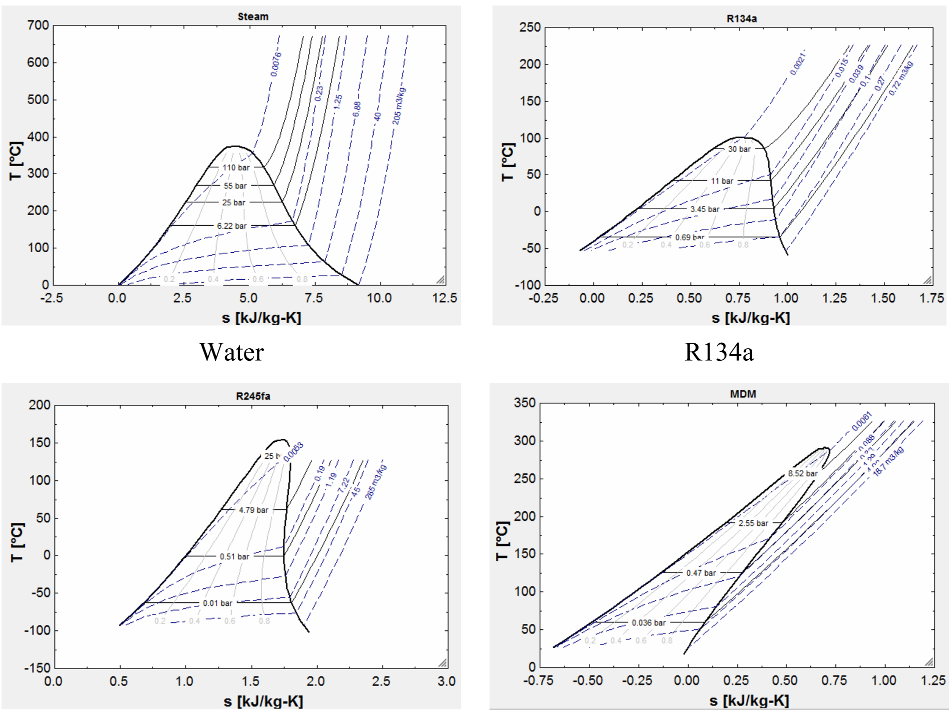
− Thermal efficiency, or mechanical efficiency) (η_m) defined as the report between the mechanical energy, or useful mechanical work (W_u) produced by the cycle and the absorbed (or consumed) energy (Q_a);

– Electric (or global) efficiency (η_e) defined as the report between the electric energy produced by the cycle (E_e) and the absorbed (or consumed) energy (Q_a) (Angelino *et al*., 1984).

The mathematical relations of the two parameters of performance are:

$$\eta_m = \frac{W_u}{Q_a}\,;\ \eta_e = \frac{E_e}{Q_a}\,. \tag{1}$$

The thermodynamic diagrams temperature - entropy (T-s) for the water, for the refrigerants R134a and R245fa and for the siloxane MDM are presented in Fig. 3. The diagrams were realised with the programming environment Engineering Equation Solver (***EES***), for which the Technical University of Cluj-Napoca is holding academic licence (Klein, 2011).



Water R134a

R245fa MDM

Fig. 3 – The T-s diagrams for water and some organic agents.

Due to the different thermal and chemical properties, the organic fluid presents both advantages and disadvantages comparing to the water. In Table 1 are presented the advantages of ***ORC*** and ***SRC*** cycles.

Table 1
Advantages of ***ORC*** *and* ***SRC*** *Cycles*

Advantages of ***ORC*** cycle	Advantages of ***SRC*** cycle
Low temperature of the hot source	High efficiency
Low evaporating temperature and pressure	Low cost of working agent
No need of superheating	Working agent is ecologic
Simple construction of evaporator	Working agent is non-toxic
Low temperature of vapours in turbine	Working agent is non-inflammable
High condensing pressure	Chemical stability of working agent
Compact construction (high density of the agent)	Low energy consumption in pump
No need for water treatment and degassing	
Relative simple design of expanders	

For the operation of the ***ORC*** equipment can be used very different energy sources, from the geothermal energy of low thermal potentials and from solar energy to the burning gases or steam over (250-300)°C (Siva Reddy *et al*., 2013; Badr *et al*., 1984; Badr *et al*., 1990).

One of the ***ORC*** systems operating with very low thermal potential heat source is located in Chena Hot Springs, Alaska, USA and is powered by geothermal water with 73°C at the inlet and 54°C at the outlet (Brasz *et al*., 2005; Cogswell, 2006; Erkan *et al*., 2007; Lund, 2006).

3. Method

The external working conditions of the ***ORC*** equipment are the hot source temperature and the cold source temperature. In this study it was considered that hot source is the hot water from a geothermal source or prepared by a solar thermal system, and the cold water is the cooling water from a closed circuit equipped with a cooling tower.

The internal working conditions, represented by the refrigerant temperatures and pressures were calculated based on the thermal regime of the evaporator and of the condenser, presented in Figs. 4 and 5. In this study the refrigerant was considered R245fa.

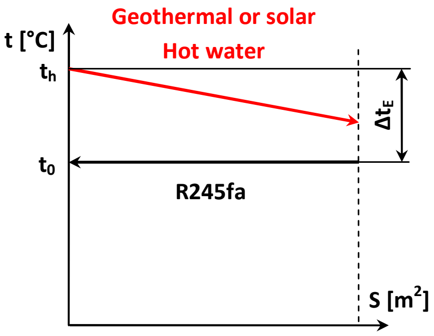


Fig. 4 – Thermal regime of evaporator
Δt_E – Total temperature difference in evaporator;
t_0 – Evaporating temperature

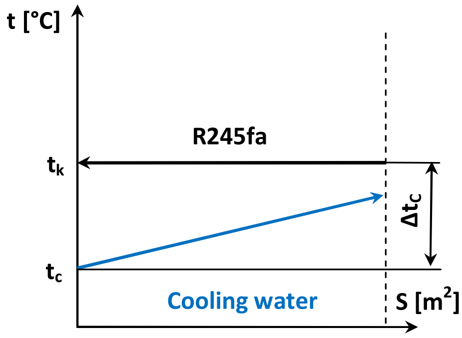


Fig. 5 – Thermal regime of condenser
Δt_c – Total temperature difference in condenser;
t_k – Condensing temperature

The evaporating temperature (t_0) and the condensing temperature (t_k) can be calculated with the following relations:

$$t_0 = t_h - \Delta t_E. \tag{2}$$

$$t_k = t_c + \Delta t_C. \tag{3}$$

where Δt_E is the total temperature difference in the evaporator and Δt_C is the total temperature difference in the condenser. Both temperature differences were considered of 10°C (Badr *et al*., 1984; Badr *et al*., 1990; Nusiaputra *et al*., 2014).

Based on the evaporating and condensing temperatures, were calculated the corresponding saturation pressures and then, all the thermal parameters in all the representative thermal states of the cycle.

The ***ORC*** cycle was calculated based on energy balance equations, for each of the main components of the equipment. The electric power (P_{el}) was considered as input data and flow rate ($\dot{m}$) could be thus calculated.

$$\dot{m} = P_{el} \Big/ \left[\eta_g \cdot \eta_x \cdot \left(h_2 - h_3 \right) \right], \tag{4}$$

where η_g is the efficiency of the electric generator (in this study 0.8) and η_x is the efficiency of the expander (in this study 0.65) (Badr *et al.*, 1984; Badr *et al.*, 1990; Nusiaputra *et al*., 2014).

The thermal or mechanical powers of the main components were calculated.

The thermal power of the evaporator ($\dot{Q}_0$) is:

$$\dot{Q}_0 = \dot{m} \cdot (h_2 - h_1). \tag{5}$$

The thermal power of the condenser ($\dot{Q}_c$) is:

$$\dot{Q}_c = \dot{m} \cdot (h_3 - h_4). \tag{6}$$

The mechanical power of the expander (P_m) is:

$$P_m = \dot{m} \cdot \eta_x \cdot (h_2 - h_3). \tag{7}$$

The mechanical power of the pump (P_p) is:

$$P_p = \dot{m} \cdot (h_1 - h_4)/\eta_p , \tag{8}$$

where η_p is the efficiency of the compression (in this study 0.75) (Badr *et al.*, 1984; Badr *et al.*, 1990; Nusiaputra *et al.*, 2014).

The calculation of the ***ORC*** cycle was implemented in ***EES***. All the calculations were performed for the temperature of the hot source and for the electric power in the mentioned ranges.

The results were processed in Excel to provide an equation capable to model the dependence of the needed thermal power ($\dot{Q}_0$) by the requested electric power (P_{el}) and by the available temperature of the hot source (t_h).

4. Results

The calculations were performed for the electric powers: (0.5; 1; 1.5; 2, 2.5; 3; 3.5; 4 and 4.5) kW and for the temperatures of the hot source (80; 90; 100; 110 and 120)°C.

As example, some of the results obtained for t_h = 120°C are presented in Table 2.

Table 2
*Example of Results for the **ORC** Cycle Calculations* (t_h = 120°C)

P_{el} [kW]	$\dot{m}$ [kg/s]	$\dot{Q}_0$ [kW]	η_e [-]
1	0.05	12.12	0.08
2	0.10	24.23	0.08
3	0.16	36.35	0.08
4	0.21	48.46	0.08

The obtained values of the electric or global efficiency of the ***ORC*** equipment ($\eta_e \approx 8\%$) is in good agreement with the data provided by the literature (Badr *et al.*, 1984; Badr *et al.*, 1990; Brasz *et al.*, 2005; Cogswell, 2006; Erkan *et al.*, 2007; Lund, 2006; Nusiaputra *et al.*, 2014).

The data processing revealed that the dependence of needed thermal power ($\dot{Q}_0$) by the requested electric power of the ORC equipment (P_{el}) is linear:

$$\dot{Q}_0 = a \cdot P_{el} \,. \tag{9}$$

The coefficient (a) presents a polynomial variation of second order with the temperature of the available hot source (t_h):

$$a = 0.0041 \cdot t_h^2 - 1.0418 \cdot t + 77.583 \,. \tag{10}$$

By combining eqs. (9) and (10) it was obtained the dependence of needed thermal power ($\dot{Q}_0$) by the requested electric power (P_{el}) and by the available hot source temperature (t_h).

$$\dot{Q}_0 = \left(0.0041 \cdot t_h^2 - 1.0418 \cdot t + 77.583\right) \cdot P_{el} \,. \tag{11}$$

The eq. (11) was calculated by regression with a confidence of 95% and with the coefficient of determination $R^2 = 0.9982$.

The results of calculations with eq. (11) are presented in Fig. 6.

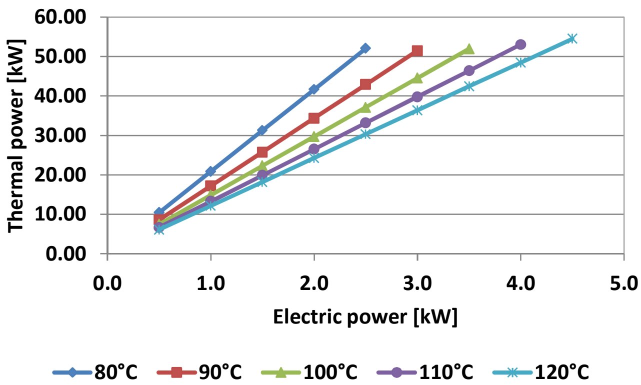


Fig. 6 − Results of calculations with the provided model.

As expected, the needed thermal power was obtained as a family of straight lines.

This equation can be used on one side in the calculation of needed thermal power to operate low temperature and small size ***ORC*** equipment and on other side in simulations of the behaviour of low temperature and small size ***ORC*** equipment under variable electric power request (typical situations for real applications) and under temperature variations of available hot source (typical situations for solar powered ***ORC*** equipment).

5. Conclusions

The study was conducted by numerical simulation and provided an analytical model capable to characterise the variation of the needed thermal power function of variable electric power of the ***ORC*** equipment and of a variable temperature of available hot source. By the knowledge of authors, this kind of model is original, being not available in the literature.

The study was realised assuming values for the total temperature differences in the evaporator and condenser and for the different efficiencies, recommended by the available literature.

The value of the obtained electric efficiency (around 8%) is in good agreement with available literature.

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MODEL PENTRU COMPORTAREA UNUI ECHIPAMENT ORC DE DIMENSIUNI REDUSE CARE FUNCȚIONEAZĂ LA TEMPERATURI SCĂZUTE

(Rezumat)

Studiul prezintă informații specifice privind teoria şi modul de funcționare a echipamentelor de mică putere electrică, funcționând după ciclul Rankyne cu fluide organice: siloxani, (substanțe cu legături chimice Si–O–Si), hidrocarburi, sau agenți frigorifici.

Este prezentat algoritmul de calcul termic al ciclului Rankine cu fluide organice şi este prezentat un exemplu de calcul, realizat cu programul Engineering Equations Solver (EES), pentru care Universitatea Tehnică din Cluj-Napoca deține licență academică. În toate situațiile valoarea obținută pentru randamentul electric global este de ≈8%, fiind în concordanță cu literatura ştiințifică.

Cel mai important rezultat al studiului, este ecuația care modelează comportarea unui echipament fucționând după ciclul Rankine organic, care permite calcularea puterii termice necesare în funcție de puterea electrică instantanee şi de temperatura sursei calde disponibile.