EFFECT OF SUPERHEATING DEGREE AND PRESSURE ON EFFICIENCY OF AN ORES (ORGANIC RANKINE ENERGY STORAGE) SYSTEM

M. M. D. O. Júnior[a]

A. A. T. Maia[b]

M. P. Porto[c]

Universidade Federal of Minas Gerais

Graduate Program in Mechanical Engineering

[a]maurymoj@gmail.com

[b]aamaia@demec.ufmg.br

[c]matheusspporto@gmail.com

ABSTRACT

The increased share of intermittent renewable energy sources has led to the development of new energy storage solutions to mitigate the effects of the variability of energy supply. CAES (Compressed Air Energy Storage) and LAES (Liquid Air Energy Storage) are two of the main solutions for medium to large-scale systems for long-term energy storage. However, both are limited; the first requires the availability of suitable geological formations and the second requires considerable investment because of the required liquefaction process. This work aims to evaluate the thermodynamic performance of an energy storage system, called Organic Rankine Energy Storage (ORES), with a focus on the effects of pressure and superheating degree at the expander inlet on the round-trip efficiency (i.e. ratio of generated energy during energy discharge over consumed energy during energy storage) of the system. The system was evaluated for six organic fluids which were selected based on commercial maturity, environmental impacts, and safety conditions, namely R-134a, R-152a, R-142b, R-236ea, R-365mfc, and R-141b. The efficiency of the system was obtained for each of those fluids using a steady-state model approximation of the operation of the system and for pressures at the expander inlet varying from 675 kPa up to 4,300 kPa (or 95% of the critical pressure, if lower) and for superheating degrees from 0 up to 40 K. The evaluation of the system for six organic fluids as working fluid resulted in round-trip efficiencies around 70 % (comparable to both CAES and LAES when subject to similar methodologies) with higher sensitivity to pressure than to superheating degree. For all fluids, an increase of 5 K in the superheating degree resulted in an absolute decrease of 2-5% in the round-trip efficiency. Effects of pressure were more diverse, R-152b, R-134a and R-142b showed an average reduction of 10% in efficiency for each reduction of 500 kPa in pressure (in the high efficiency operation region, while R-365mfc and R-141b were much less affected, around 5% decrease in efficiency for each reduction of 500 kPa. The fluids that had the highest efficiencies and that also presented a high efficiency for a wider range of pressures were the R141b and R365mfc, which are also the fluids with the highest critical temperatures.

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INTRODUCTION

The increased effects of climate change on everyday life have led to an increased focus on the development and deployment of renewable energy sources leading to high levels of renewable energy penetration (IRENA, 2019). However, most of these sources, e.g., solar and wind energy, are characterized by an intermittent supply of energy, which results in increased challenges for energy management services. In the earlier stages of renewable energy penetration (up to 10-20%) this characteristic pose little threat for energy supply and can be managed with the control systems already present in most grids. However, as intermittent renewable energy sources become a larger fraction of the energy matrix, further attention must be given in order to ensure quality and safety of the energy supply. Currently, one of the main solutions is the incorporation of energy storage systems with the exclusive purpose of managing the surplus energy generated by intermittent sources for periods with higher demand. Cebulla *et al*. (2018) have shown that as intermittent renewable energy share increases, the demand for energy storage systems increases linearly in terms of power capacity and exponentially in energy capacity.

Currently, PHES (Pumped Hydro Energy Storage) represents most of the installed energy capacity worldwide, mostly due to its relative low cost and high energy and power capacity coupled with low self-discharge rate and long lifetime (Steinmann, 2017). A few alternative energy storage solutions have been proposed for medium and large-scale energy storage such as LAES (Liquid Air Energy Storage) and CAES (Compressed Air Energy Storage). However, both have their shortcomings. As LAES requires cryogenic liquefaction of air it has limitations regarding efficiency and, most importantly, system cost (Georgiou *et al*., 2018). On the other hand, CAES operates at reasonably high pressures (40-80 bar) with a low-density fluid demanding a large pressure vessel which must withstand these levels of pressure, resulting in expensive artificial tanks. Therefore, the installation of CAES systems frequently requires the availability of a suitable geological formation (Steinmann, 2017; Chen *et al*., 2017 and Krawczyk *et al*., 2018).

The objective of this study is to evaluate the performance of an energy storage system based on the ORC (Organic Rankine Cycle), named ORES (Organic Rankine Energy Storage) and the effect of the pressure at the discharging line and the superheating degree in the efficiency of the system.

THERMODYNAMIC ANALYSIS

System Description

The operation of the system can be divided in two parts: energy storage and energy generation. The system operates in a closed cycle with a section active during one stage while the other is inactive and the opposite during the other process, the common elements in both processes being the two storage tanks, the HPT (High Pressure Tank) and the LPT (Low Pressure Tank). During energy storage the available energy is fed into a pump that increases the pressure of the fluid, in liquid state, before it enters a heater until it reaches the state of saturated liquid and is loaded into the HPT. During the energy generation process the fluid in the HPT goes through an evaporator, goes through an expander, generating energy, and is cooled down to the state of saturated liquid, returning to the LPT. The basic schematic for the ORES system is shown in Fig. 1.

Thermodynamic model

The description of the model of the system will be divided in two parts, the first will describe the model for the energy generation process and the second part the energy storage process. Figures 2 and 3 illustrate the operation and thermodynamic states considered for the energy generation and storage models, respectively.

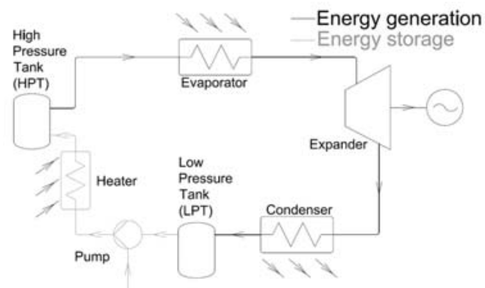


Figure 1. Basic schematics for the ORES system.

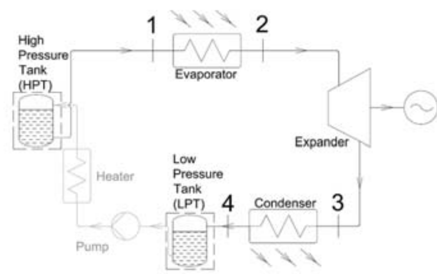


Figure 2. ORES discharging process.

The specific heat required in the evaporator q_{ev}, the specific power generated in the expander w_{exp} and the heat removed in the condenser q_{cond} can be obtained from energy balances at each component, respectively, Eqs. (1), (2) and (3).

$$\mathrm{q_{ev}} = \mathrm{h_2} - \mathrm{h_1}, \tag{1}$$

$$\mathrm{w_{exp}} = \mathrm{h_2} - \mathrm{h_3}, \tag{2}$$

$$\mathrm{q_{cond}} = \mathrm{h_3} - \mathrm{h_4}, \tag{3}$$

where h is the specific enthalpy at each point, $\mathrm{h_3}$ can be estimated with the definition of expander isentropic efficiency, assuming the efficiency η_{exp} is known, Eq. (4)

$$\mathrm{h_3} = \mathrm{h_2} - \eta_{\mathrm{exp}}(\mathrm{h_2} - \mathrm{h_{3,s}}), \tag{4}$$

where $\mathrm{h_{3,s}}$ is the specific enthalpy at the expander exit for an isentropic efficiency. The mass flow rate during energy generation, $\dot{\mathrm{m}}_{\mathrm{EG}}$, can be obtained as a function of the required power output, $\dot{W}_{\mathrm{exp}}$, Eq. (5),

$$\dot{m}_{EG} = \frac{\dot{W}_{exp}}{w_{exp}}. \quad (5)$$

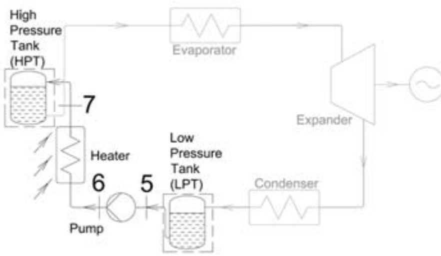


Figure 3. ORES charging process.

During energy storage the working fluid is pumped from the LPT through a heater and into the HPT. The specific work in the pump w_p and heat in the heater q_H can be obtained with energy balances at each component, Eqs. (6) and (7),

$$w_p = h_6 - h_5, \quad (6)$$

$$q_H = h_7 - h_6. \quad (7)$$

The enthalpy at the pump outlet h_6 is obtained with the definition of isoentropic efficiency, assuming the isoentropic efficiency η_p is known, Eq. (8),

$$h_6 = h_5 + \frac{h_{6,s} - h_5}{\eta_p}, \quad (8)$$

where $h_{6,s}$ is the enthalpy at the pump outlet for a isoentropic compression. Finally, the mass flow rate during energy storage, $\dot{m}_{ES}$, can be obtained as a function of the available power input, $\dot{W}_p$, Eq. (9),

$$\dot{m}_{ES} = \frac{\dot{W}_p}{w_p}. \quad (9)$$

The ORES system requires available heat during both processes, energy generation and storage, in this paper the heat was assumed to be provided by two heat pumps, HP_{EG} and HP_{ES}, respectively. The power consumed in both heat pumps can be obtained from the definition of coefficient of performance, Eq. (10) and (11),

$$W_{HP,ES} = \frac{Q_H}{COP_{HP,ES}}, \quad (10)$$

$$W_{HP,EG} = \frac{Q_{ev}}{COP_{HP,EG}}. \quad (11)$$

Energy storage systems are usually evaluated in terms of the round-trip efficiency, η_{RT}, which is defined as the ratio of net energy generated during the discharging phase over the energy consumed during energy storage (Aneke and Wang, 2016). For the case of ORES coupled with two heat pumps the round-trip efficiency is given by Eq. (12),

$$\eta_{RT} = \frac{W_{exp} - W_{HP,EG}}{W_p + W_{HP,ES}}. \quad (12)$$

METHODOLOGY

A total of six organic fluids were selected based on their broad use on current ORC's, also safety conditions (flammability and toxicity) and environmental impacts (Ozone Depletion Potential - ODP - and Global Warming Potential - GWP) (Bao and Zhao, 2013; Xi *et al.* 2015; Aneke and Wang, 2016; Hærvig *et al.*; 2016, Xu *et al.*, 2016 and Su *et al.* 2018). The main properties of these organic fluids are displayed in Tab. 1.

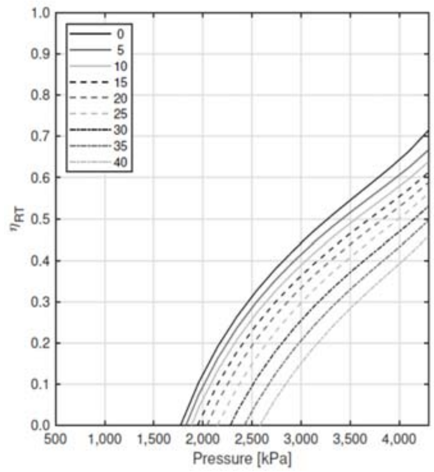
Table 1. Properties of the evaluated working fluids.

Fluid	Molar mass [kg/kmol]	T_{crit} [ºC]	P_{crit} [kPa]	ODP	GWP (100yr)
R-134a	102.03	101.00	4,059	0	1430
R-152a	66.05	113.30	4,520	0	124
R-142b	100.50	137.11	4,055	0.070	2310
R-236ea	152.04	139.30	3,420	0	1200
R-365mfc	148.08	186.85	3,226	0	794
R-141b	116.95	204.20	4,249	0.120	725

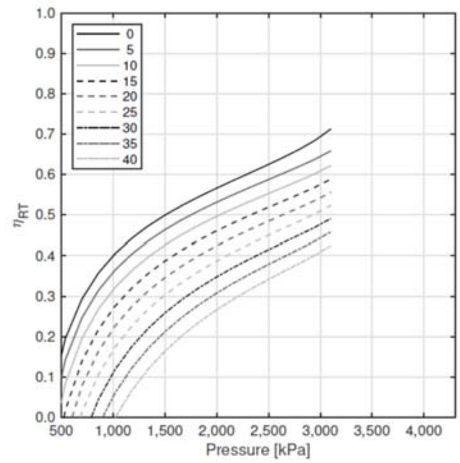
The round-trip efficiencies will be calculated for each working fluid, for HPT pressures ranging from 675 kPa up to 4.300 kPa (or 95 % of the critical pressure, if lower) and superheating degree ΔT_{SH} from 0 K up to 40 K, in steps of 5 K. The simulations were carried out considering steady-state operation. Despite the inherent transient characteristic of charging and discharging of tanks the approximation of steady state provides reasonable results at a much lower computational cost (Wang et al., 2015 and Venkatarami et al., 2019). The ORES system was evaluated considering an expander power of 1,000 kW and 200 kW for the pump, isentropic efficiencies of 80 % and 75 % for the expander and for the pump, respectively (Lecompte et al., 2015 and Hærvig et al., 2016). The temperature at the LPT was set at ambient temperature. Pressure losses were considered negligible. The model of the system was implemented in MATLAB with the use of the CoolProp external library (Bell et al., 2014).

3. RESULTS

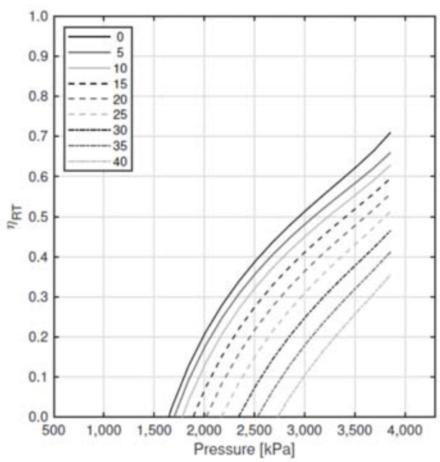
The results of round-trip efficiency for each fluid for varying values of pressure at the HPT and superheating degree are shown in Figure 4.



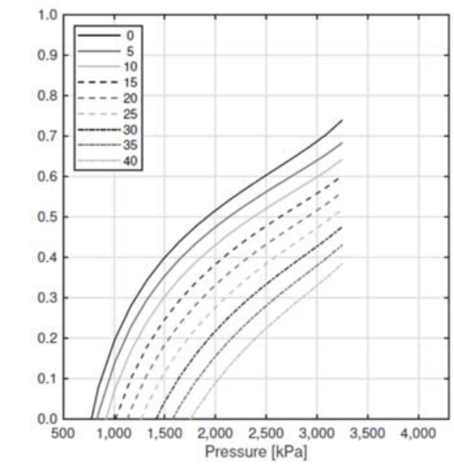
(a) R-152a



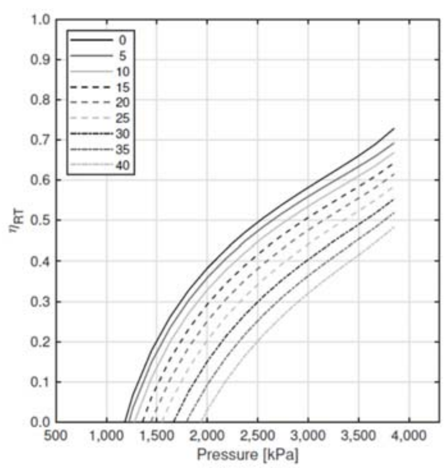
(d) R-365mfc



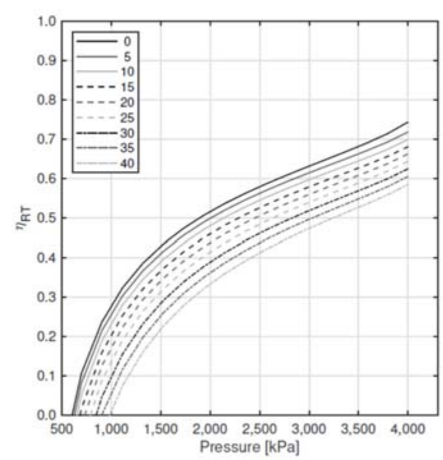
(b) R-134a



(e) R-236ea



(c) R-142b



(f) R-141b

Figure 4. Round-trip efficiency as a function of pressure at the HPT and superheating degree [K] for each evaluated working fluid.

For all fluids a combination of high storage pressure and low superheating degree resulted in the highest values of round-trip efficiency. The maximum round-trip efficiency of the evaluated fluids ranged from 71 % for R152a up to 74 % for R141b. For most fluids η_{RT} decreased linearly with the increase of the superheating degree, except for R152a, that showed increased gradients for higher superheating degrees. In general, an increment of 5 K in the superheating degree resulted in an absolute 3-5 % reduction in the round-trip efficiency, except for R141b, which showed a reduction of 2 % for each increment. The most relevant difference between the evaluated fluids was the variation of η_{RT} with P_{HPT} . R152a, R134a, R142b and R236ea have an average reduction of 10 % in η_{RT} for each reduction of 500 kPa in P_{HPT} for the higher values of efficiency, while R365mfc and R141b are much less affected to the variation in pressure, which translates into a wider range of pressures with a positive round-trip efficiency. This suggests that, over the discharging or charging phase of the energy storage system, as pressure in both tanks change due to the transient states inherent to both processes, the performance of the system is more stable while also allowing for a higher discharge of the storage tank, that can now discharge to lower pressures.

In order to better compare the performance of the evaluated fluids the curves of η_{RT} for $\Delta T_{SH} = 0$ K as a function of pressure is shown in Fig. 5.

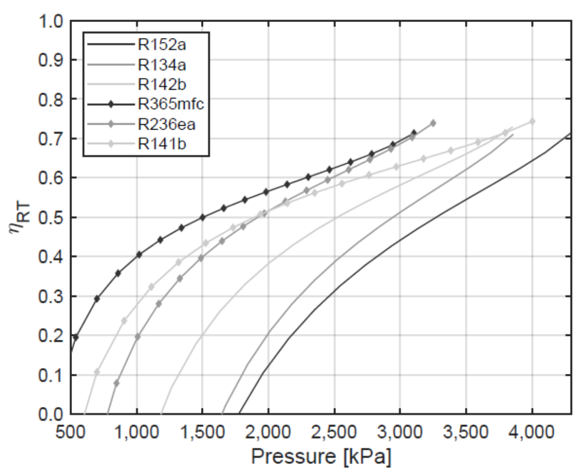


Figure 5. Round-trip efficiency as a function of pressure at the high-pressure storage tank with superheating degree equal to 0 K.

Figure 5 shows more clearly the difference in performance among working fluids, with only one intersection between the curves for R236ea and R141b, and a clear superiority, in terms of η_{RT}, for R365mfc. It should be noted that R141b maintains a roundtrip efficiency over 50 % for a wide range of pressure values, from 2 MPa up to 4 MPa, suggesting a good transient performance.

CONCLUSIONS

This study evaluated the performance of the ORES system with a focus on the effects of pressure during discharge and superheating degree on the round-trip efficiency. The system was evaluated considering steady-state operation for the study of six commonly used organic fluids with favorable safety and environmental characteristics.

Round-trip efficiency was reasonably more sensible to changes in the pressure at the HPT than in superheating degree with the highest round-trip efficiencies found for the lowest superheating degree ($\Delta T_{SH} = 0$) and highest pressure. Regarding the evaluated fluids, all presented maximum η_{RT} over 70 %, indicating the competitiveness of the ORES system despite the operation at much lower pressures. The most noticeable differences between the evaluated fluids regards to the range of pressure values over which the system maintains a high η_{RT}. Whilst R-141b maintained $\eta_{RT} > 50$ % for $1{,}750 < P_{HPT} < 4{,}000$ kPa, R-134a would only maintain this level of efficiency for $3{,}000 < P_{HPT} < 3{,}800$ kPa. As during a real operation of the ORES system the pressure would decrease as the tank is discharge this behavior reflects the acceptable depth of discharge in order to maintain a certain efficiency whilst supplying the required energy.

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