Comparison of Different Working Fluids Operation for Basic and Modified Organic Rankine Cycles (ORCs)

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This paper presents a theoretical framework for selecting of appropriate working fluids for basic Organic Rankine Cycle (ORC) and three modified ORCs based on their thermodynamic properties. A comprehensive thermodynamics analysis is done for basic ORC, modified ORC incorporating turbine bleeding, regenerative ORC, and ORC incorporating both turbine bleeding and regeneration using 8 different working fluids (R113, R141b, n-pentane, R123, R245fa, R600, isobutane, R236fa). Among these analyzed working fluids, R113 and R236fa present the highest and lowest thermal efficiency. The thermal efficiency can be much higher when the modified ORC incorporating both turbine bleeding and regeneration is used. Of course, among of the presented working fluids, there are environmentally-friendly working fluids, too, which can be a good choice for the environmentally consideration issues. At the end, we will also present a parametric study for crucial parameters in the cycle. With this study, we can find a specific range for the evaporator pressure in which the condenser duty and net produced power will be minimum and maximum, respectively. In fact, we will present an optimum value for the pressure of evaporator using different working fluids for the purpose of the condenser duty minimization and the net produced power maximization. The optimum value for the pressure of the evaporator in this case will range from 2.778 to 3.656 MPa.

keywords: *Organic Rankine Cycles (ORCs), Working fluid, Thermodynamics analysis, Environmentally- friendly, Parametric study.*

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NOMENCLATURE

A. Symbols:

h specific enthalpy $(kJ.kg^(-1))$

$\dot(m)$ mass flow rate $(kg.s^(-1))$

ORC organic Rankine cycle

P pressure (MPa)

$\dot{Q}$ heat transfer rate ()

s specific entropy $(kJ.kg^(-1).K^(-1))$

T temperature (K)

v specific volume (m^3.$kg^(-1)$)

$\dot{W}$ power (kW)

B. Greek Symbols:

η efficiency (%)

α compressor compression ratio

C. Subscripts and supersc ripts:

b boiler

c condenser

d destruction

e evaporator

ex exergetic

F fuel

FFH feed fluid heater

IHE internal heat exchanger

in inlet

int intermediate

is isentropic

L loss

net net value

ORC organic Rankine cycle

t turbine

v vapor

1,2,3,.. cycle locations

1. INTRODUCTION

In recent years, energy researches have been gone further because of an increasing demand for different energy resources such as coal, petroleum, natural gas or more importantly zero polluted resources such as solar energy, geothermal, biomass, and so on. So, more attempts are made to maximize the performance of the cycles by different approaches. In addition to the escalating global energy demands, these approaches are aimed to introduce new sustainable schemes in energy domain.

In recent decades, the Organic Rankine Cycle (ORC) on account for its capability to converts low-grade heat to electric power has been emerged as a cycle with a high efficiency. Its mission is reducing of greenhouse gas emission, offering an easier implementation in local power generation systems, and so on. The structure of ORC is the same as Rankine cycle except that its working fluid instead of water is organic fluid. In reality, this is the reason behind of this cycle utilization by the low-grade heat resources.

In the recent years, ORC has been evaluated by various methods. Such a these methods are: selection of optimum value parameters, selection of appropriate working fluids, thermo-economically cycle analysis, a novel integration of this cycle by different refrigeration cycles for cogeneration of power and cooling purposes, and so on. Among these factors, selection of a proper working fluid can lead to a high thermodynamics performance, and more importantly, low environmental impact which the cycle can be caused. There have been a numerous studies on these issues, which can be pointed out in here. Wang et al. [1] presented a mathematical models to simulate low-grade solar-drive regenerative ORC at steady-state conditions. Their results indicated that increasing of turbine inlet temperature and pressure will improve the cycle performance. They were also shown that R245fa and R123 are the most appropriate working fluids for the ORC due to their high thermodynamics performance. Kumar and Shukla [2] described benzene as a suitable working fluid for the ORC on account of its better economical achievement. They also found that for 8 kW of power output, the ORC efficiency will be in the range of 29.19 to 48.84% with respect to the mass flow rate variation. Garg et al. [3] studied the evaluation of hydrocarbons and carbon dioxide as a mixture working fluids in the ORC based on the solar power applications. In their model major cause of irreversibility had been introduced by the shift of the pinch point towards the warm end of the regenerator. Barse and Mann [4] compared the constrained system performance with non-constrained system performance by 12 working fluids. They concluded that using working fluids with lower critical temperatures at non-constrained system do not show significant improvement in performance. Delgado-Torres and Garcia-Rodriguez [5] expanded some theoretical analysis for solar-driven ORC by means of stationary solar collectors. They selected four different working fluids (butane, isobutane, R245ca, and R245fa) out of 12 considered working fluids for their analysis. Safarian and Aramoun [6] presented an energetic and exergetic analysis of basic as well as three modified ORCs using R113 as a working fluid. They demonstrated that ORC incorporating both turbine bleeding and regeneration has the highest thermal and exergetic efficiency. Karellas and Braimakis [7] investigated thermodynamics and economic analysis on the integrated Organic Rankine Cylce (ORC) and Vapor Compression Cycle (VCC) based on the utilization of biomass and solar energy. Their analysis demonstrated that the thermal efficiency of the proposed cycle will be maximized when using R245fa as a working fluid. Feng et al. [8] compared ORCs operation based on the pure and mixture working fluids utilization from thermoeconomic point of view. They demonstrated that mixture working fluids don't always present higher performance than pure ones. Kang [9] conducted an experimental study on ORC which generates electric power using R245fa as an environmentally-friendly working fluid. They introduced factors which influence the performance of developed ORC and can optimize ORC operation in the next works. Le et al. [10] optimized the performance of subcritical ORC using two pure organic fluids, i.e. R245fa and n-pentane and their mixtures, thermodynamically and economically. They demonstrated that the pure fluids present higher thermodynamic performances.

Among all well-known cycles, using organic Rankine cycle (ORC) is a promising way to use low-grade heat sources in recent researches [11–14]. The operation of the ORC can be also improved by applying eco-friendly working fluids which has been highlighted from its beginning [15–17]. Yari [18] compared various geothermal power plants concepts, based upon the exergy analysis for high-temperature geothermal resources. He showed that the maximum thermal efficiency for ORC with an IHE, binary cycle with the regenerative ORC with an IHE, and with flash-binary using R123 as a working fluid are 7.65, 15.35, and 11.81%, respectively. Safarian and Aramoun [19] expressed a theoretical analysis of modified organic Rankine cycles (ORCs) based on the 1st and 2nd laws of thermodynamics, using R113 as working fluid. They showed that ORC with both turbine bleeding and regeneration has the highest thermal and exergy efficiencies. They had also concluded that the evaporator has the main contribution in the overall exergy destruction which can be improved by increase in the evaporator pressure. Maizza et al. [20] conducted an investigation on the physical and thermodynamical properties of some unconventional fluids for the ORC supplied by the waste energy sources. They compared thermodynamic results for each working fluid. They had also expressed analytical criteria for selection of optimal working fluid based on the thermodynamic characteristics. Some of the sub-objectives of the present paper are multi-fold and consist:

- To analyze proposed cycles based on the first and second laws of the thermodynamics.
- To introduce more appropriate working fluids based on the classical laws.
- To perform sensitivity analysis of different parameters for various cycles and working fluids.

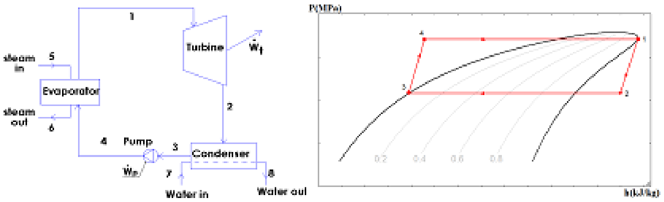

Fig. 1. Schematic diagram of: (a) basic ORC and (b) the corresponding P-h diagram.

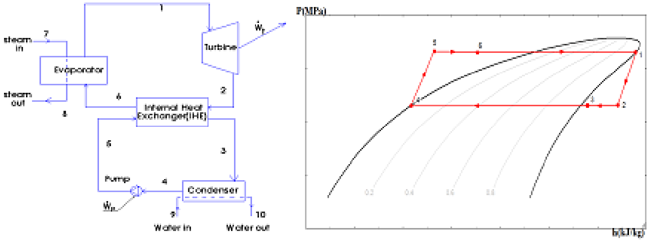

Fig. 2. Schematic diagram of: (a) modified ORC incorporating turbine bleeding and (b) the corresponding P-h diagram.

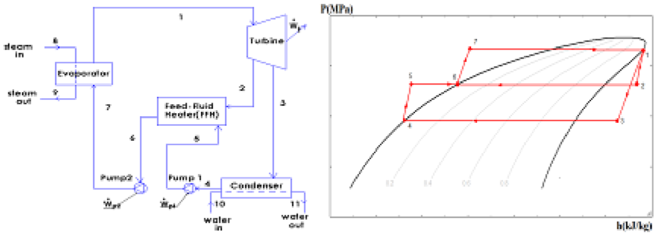

Fig. 3. Schematic diagram of: (a) regenerative ORC and (b) the corresponding P-h diagram.

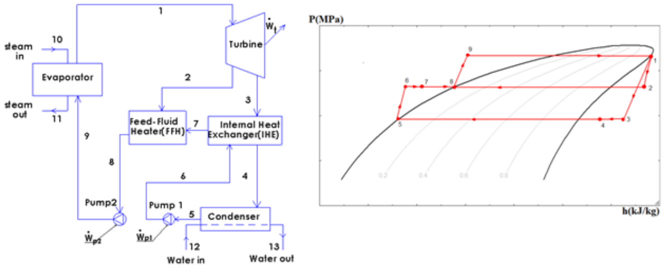

Fig. 4. Schematic diagram of: (a) modified ORC incorporating both turbine bleeding and regeneration and (b) the corresponding P-h diagram.

2. SYSTEM EVALUATIONS

The schematic of ORCs and P-h diagrams for basic ORC as well as modified ORC incorporating turbine bleeding, regenerative ORC, and modified ORC incorporating both turbine bleeding and regeneration have been shown in Figs 1- 4, respectively. The applicable components in these cycles are: evaporator, condenser, pumps, turbine, Internal Heat Exchanger (IHE), and Feed-Fluid Heater (FFH).

Table 1. Some of the required input parameters for thermodynamics analysis of the ORCs.

Parameter	Value
Evaporator pressure $P_e(MPa)$	2.8
Intermediate pressure $P_{int}(MPa)$	1
Condenser pressure $T_c(K)$	300
Mass flow rate of water $\dot{m}_W(Kg/s)$	0.7
Mass flow rate of steam $\dot{m}_s(Kg/s)$	0.4

3. THERMODYNAMICS APPROACH

A. Thermodynamics assumptions

In order to have a simple and straightforward model, it is vital to consider a couple of assumptions. These thermodynamics assumptions are as follow:

- All processes of components in the cycles are at steady state.
- Input parameters of the evaporator, condenser, IHE, pumps, and FFH are fixed at a constant value.
- Kinetic energy at the inlet and outlet of all components are negligible.
- Pressure and heat losses inside the evaporator, condenser, IHE, FFH, and ducts are negligible.
- The isentropic efficiency of the turbine and pumps are taken as 95% and 80%, respectively.
- Inlet and outlet pressure of water and steam are assumed 0.101 MPa.
- Inlet temperature of water and steam and outlet temperature of steam are taken 276 K, 400 K, and 350 K, respectively.
- Ideally, the outlet of the FFH is considered to be saturated liquid.

For thermodynamics analysis, we have developed a thermodynamics code on Engineering Equation Solver (EES), which is in a good agreement with works of other authors. Beside of these aforementioned assumptions, we need input parameters for analysis of our cycles. These parameters are given in Table 1.

B. Thermodynamics analysis

For thermodynamics analysis it is sufficient to apply governing equations (conservation of mass and energy) to each component. These governing equations for thermodynamics analysis of a cycle can be expressed in the form of equations (1) and (2).

$$\sum m_{in} - \sum m_{out} = 0 \ , \tag{1}$$

$$\sum (mh)_{in} - \sum (mh)_{out} + \sum Q_{in} - \sum Q_{out} + W = 0. \tag{2}$$

These mentioned relations are needed to be applied to each component of the ORCs. Some of the required thermodynamics balance equations in this analysis have been tabulated in Table 2 & 3.

Table 2. Some utilized equations in the thermodynamics analysis of basic and incorporating turbine bleeding

Component	Basic ORC	ORC incorporating with turbine bleeding
	Equation	Equation
Cooling capacity of evaporator	$\dot{Q}_e = \dot{m}_1(h_1 - h_4)$	$\dot{Q}_e = \dot{m}_1(h_1 - h_6)$
Power of turbine	$\dot{W}_t = \dot{m}_2(h_1 - h_2)$	$\dot{W}_t = \dot{m}_2(h_1 - h_2)$
Power of pump	$\dot{W}_p = \dot{m}_g(h_4 - h_3)$	$\dot{W}_p = \dot{m}_3(h_5 - h_4)$
Condenser duty	$\dot{Q}_c = \dot{m}_2(h_2 - h_3)$	$\dot{Q}_c = \dot{m}_3(h_3 - h_4)$
Net power of cycle	$\dot{W}_{net} = \dot{W}_t - \dot{W}_p$	$\dot{W}_{net} = \dot{W}_t - \dot{W}_p$
Isentropic efficiency of turbine	$\eta_{is,t} = (h_1 - h_2)/(h_1 - h_{2s})$	$\eta_{is,t} = (h_1 - h_2)/(h_1 - h_{2s})$
Isentropic efficiency of pump	$\eta_{is,p} = (h_{4s} - h_3)/(h_4 - h_3)$	$\eta_{is,p} = (h_{5s} - h_4)/(h_5 - h_4)$
Thermal efficiency	$\eta_{th} = \dot{W}_{net}/\dot{Q}_\epsilon$	$\eta_{th} = \dot{W}_{net}/\dot{Q}_e$

Table 3. Some utilized equations in the thermodynamics analysis of regenerative and incorporating both turbine bleeding & regeneration ORC.

Component	Regenerative ORC	ORC incorporating with turbine bleeding and regeneration
	Equation	Equation
Cooling capacity of evaporator	$Q_e = m_1(h_1 - h_7)_e = \dot{m}_1(h_1 - h_7)$	$Q_e = m_1(h_1 - h_9)_e = \dot{m}_1(h_1 - h_9)$
Power of turbine	$\dot{W}_t = \dot{m}_1 h_1 - \dot{m} h_2 - \dot{m}_3 h_3$	$\dot{W}_t = \dot{m}_1 h_1 - \dot{m} h_2 - \dot{m}_3 h_3$
Power of pump(1)	$\dot{W}_{p1} = \dot{m}_4(h_5 - h_4)$	$\dot{W}_{p1} = \dot{m}_5(h_6 - h_5)$
Power of pump (2)	$\dot{W}_{p2} = \dot{m}_6(h_7 - h_6)$	$\dot{W}_{p2} = \dot{m}_8(h_9 - h_8)$
Condenser duty	$\dot{Q}_c = \dot{m}_3(h_3 - h_4)$	$\dot{Q}_c = \dot{m}_4(h_4 - h_5)$
Net power of cycle	$\dot{W}_{net} = \dot{W}_t - \dot{W}_{p1} - \dot{W}_{p2}$	$\dot{W}_{net} = \dot{W}_t - \dot{W}_{p1} - \dot{W}_{p2}$
Isentropic efficiency of turbine	$\eta_{is,t} = (h_1 - h_2)/(h_1 - h_{2s}) = (h_1 - h_3)/(h_1 - h_{3s})$	$\eta_{is,t} = (h_1 - h_2)/(h_1 - h_{2s}) = (h_1 - h_3)/(h_1 - h_{3s})$
Isentropic efficiency of pump(1)	$h_{is,p1} = (h_{5s} - h_4)/(h_5 - h_4)$	$h_{is,p1} = (h_{6s} - h_5)/(h_6 - h_5)$
Isentropic efficiency of pump(2)	$\eta_{is,p2} = (h_{7s} - h_6)/(h_7 - h_6)$	$\eta_{is,p2} = (h_{9s} - h_8)/(h_9 - h_8)$
Thermal efficiency	$\eta_{th} = \dot{W}_{net}/\dot{Q}_\epsilon$	$\eta_{th} = \dot{W}_{net}/\dot{Q}_\epsilon$

4. WORKING FLUID SELECTION

Selection of an appropriate working fluid can be the number one issue in improving of the thermal and exergetic efficiency of organic Rankine cycle. The appropriate working fluid can be chosen based upon two important factors: having the highest efficiency and being eco-friendly working fluid. So, we must reach to a trade-off between these two factors. One of the important alternative working fluids are HC and HFC due to their zero ODP and low GWP characteristics. But, on the other hand, HC refrigerants have flammability issues, which restrict their usages in the ORC. However, the reduction in flammability can be yielded by choosing an appropriate mechanism.

In this paper we suggest 8 appropriate working fluids (R113, R141b, n-pentane, R123, R245fa, R600, isobutane, R236fa) for thermodynamics analysis of the ORCs, theoretically. Some of these working fluids properties are tabulated in Table 4. Once we notice them, we can say that among of the presented working fluids, n-pentane, R600, and isobutane are the best choice from environmentally point of view. As we will see in the next section, n-pentane will also present high thermal efficiency, too, which can be appropriate between all aforesaid working fluids, environmentally and thermodynamically.

Table 4. Some properties for investigated working fluids.

Selected Working fluids	Chemical Formula	Critical temperature (C)	Critical pressure (bar)	Boiling point (C)	GWP	ASHARAE safety code
R113	C2Cl3F3	214.33	33.92	47.55	4800	A1
R141b	C2H3Cl2F	204.35	42.12	32	725	UNKNOWN
n-pentane	C5H12	196.55	33.7	36.1	5	UNKNOWN
R123	C2HCl2 F3	183.68	36.68	27.85	77	B1
R245fa	C3H3F5	153.867	36.51	15.3	1030	B1
R600	C4H10	152	37.96	-1	4	A3
Isobutane	CH(CH3)2CH3	134.66	36.29	-11.7	3	A3
R236fa	C3H2F6	124.92	32	-0.5	9810	A1

Table 5. Model validation of present study and reference [13] using R245fa.

Parameter	Present work	Reference [13]	Relative error (%)
Turbine expansion ratio β	3.298	3.26	1.16
Compressor compression ratio α	3.776	3.76	0.42
ORC efficiency $\eta_{ORC}(\%)$	7.824	7.77	0.69

Table 6. Output data obtained from thermodynamics analysis of basic and incorporating turbine bleeding ORC.

Working fluid	Basic ORC				ORC incorporating turbine bleeding			
	$\dot{Q}_e(KW)$	$\dot{Q}_c(KW)$	$\dot{W}_{net}(KW)$	$\eta_{th}(\%)$	$\dot{Q}_e(KW)$	$\dot{Q}_c(KW)$	$\dot{W}_{net}(KW)$	$\eta_{th}(\%)$
R113	963.3	742.1	221.1	22.96	963.3	739.7	223.6	23.21
R141b	963.3	743.4	219.9	22.83	963.3	740.6	222.7	23.12
n-pentane	963.3	753.6	209.7	21.77	963.3	750.4	212.8	22.09
R123	963.3	754.5	208.8	21.68	963.3	751.1	212.2	22.02
R245fa	963.3	786	177.3	18.4	963.3	782.5	180.8	18.77
R600	963.3	789.5	173.8	18.05	963.3	786.4	176.9	18.36
Isobutane	963.3	807.4	155.9	16.18	963.3	804.3	158.9	16.5
R236fa	963.3	816	147.2	15.28	963.3	812.4	150.9	15.66

5. RESULTS AND DISCUSSIONS

A. Model validation

For accuracy measurement of the present work, we have validated present work with the reference [21]. Under the same external conditions and considering R245fa as working fluid, the present study shows a great agreement with the aforesaid reference (Table 5). This accuracy is believed to be satisfactory in most engineering problems.

B. Thermodynamics results

Tables 6- 7 give the thermodynamics parameters obtained for basic ORC and three modified ORCs. One can say that among the investigated working fluids, R113 and R236fa show the highest and lowest thermal efficiency, respectively. At the same time, thermal efficiency also will be improved for modified ORCs, too. The range of thermal efficiency for basic ORC, ORC incorporating turbine bleeding, regenerative ORC, and ORC incorporating both of them are (15.28-22.96), (15.66-23.21), (17.51-26.05), and (17.98-26.54)%, respectively.

These highest and lowest efficiencies can be justified by the highest or lowest value of net produced power, respectively. On the other hand, we can say that R113 and R236fa have the highest and lowest net produced power, respectively. In the similar case, ORC incorporating both turbine bleeding and regeneration and basic ORC have the highest and lowest net produced power under the same conditions. The cooling capacity of the cycles which is stimulated by the hot steam is constant for each working fluid and all cycles. In other word, variation of key parameters has no effect on the cooling capacity of the ORCs.

C. Sensitivity analysis of key thermodynamic parameters

Two important parameters for the analysis of organic Rankine cycle are the outlet pressure of evaporator and outlet temperature of condenser which are analyzed in the following subsections. The investigation of parametric study for different ORCs is a cumbersome and useless effort. So, we study the effect of these key parameters on modified ORC incorporating both turbine bleeding and regenerative, and then we will extent it to the ORCs.

Table 7. Output data obtained from thermodynamics analysis of regenerative and incorporating both turbine bleeding and regeneration ORC.

Working fluid	Basic ORC				ORC incorporating turbine bleeding			
	$\dot{Q}_\epsilon(KW)$	$\dot{Q}_c(KW)$	$\dot{W}_{net}(KW)$	$\eta_{th}(\%)$	$\dot{Q}_\epsilon(KW)$	$\dot{Q}_c(KW)$	$\dot{W}_{net}(KW)$	$\eta_{th}(\%)$
R113	963.3	712.3	250.9	26.05	963.3	621.3	255.6	26.54
R141b	963.3	715.3	247.9	25.74	963.3	725.6	252.3	26.19
n-pentane	963.3	724.2	239.1	24.82	963.3	627.4	243.5	25.28
R123	963.3	726.1	237.2	24.62	963.3	712.3	241.8	25.1
R245fa	963.3	761.8	201.5	20.92	963.3	761.4	206	21.39
R600	963.3	767.1	196.1	20.36	963.3	761	200	20.76
Isobutane	963.3	787.8	175.4	18.21	963.3	807.1	179.1	18.59
R236fa	963.3	794.6	168.7	17.51	963.3	823.4	173.2	17.98

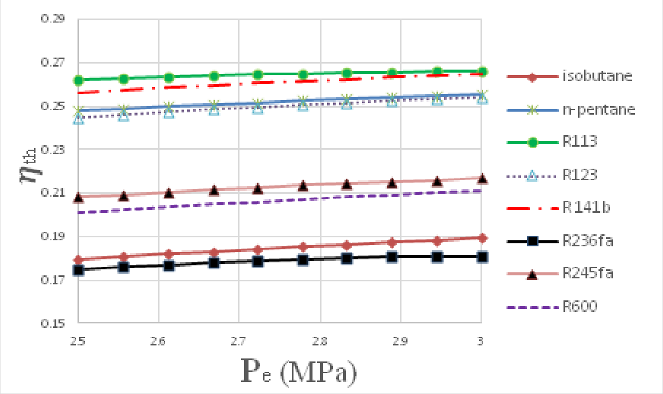

Fig. 5. The variation of the thermal efficiency versus of the evaporator pressure for different working fluids.

C.1. Effect of evaporator pressure on the ORCs

Fig. 5 illustrates the variation of thermal efficiency versus of the evaporator pressure for different working fluids. As we can see, increasing of the evaporator pressure will increase the thermal efficiency of the ORCs. The more energy evaporator gains, the more thermal efficiency the cycle can produce. This figure also illustrates that between of the compared working fluids; R113 and R236fa have the highest and lowest thermal efficiency, respectively.

C.2. Effect of condenser temperature on the ORCs

Fig. 6 illustrates the variation of thermal efficiency versus of the condenser temperature for different working fluids. As we can see, increasing of the condenser temperature will decrease the thermal efficiency of the ORCs. As pointed out earlier, this phenomenon can be explained by heat loss of the condenser during the operation of ORC.

Another important parameter for producing of power, cooling of outer cycle working fluid, for instance, is condenser duty of organic Rankine cycle. Fig.7 shows the variation of the condenser duty versus of the condenser temperature for different working fluids. Obviously, reduction of the condenser temperature will reduce the condenser duty, considerably.

D. Minimization of the condenser duty

It is very efficient to decrease the duty of condenser in the ORC by different means, as one can figure out this fact from tables 6-7 in section B. This drawback of the ORC (losing of heat without any exploitation) can be enhanced by different ways. Cogeneration of cooling and power is one of the interested ways with regard of another appropriate cycle for power generation purposes. However, it is much more complicated and expensive in applications. Another simple way can be implemented in such a way that will minimize the condenser duty. This optimization can be achieved by choosing of the suitable values for key parameters.

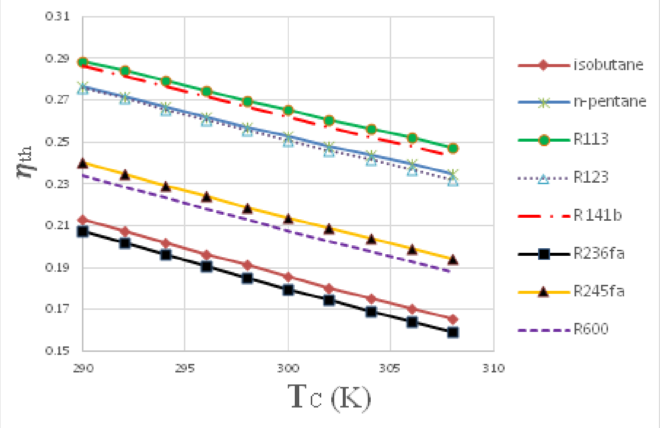

Fig. 6. The variation of the thermal efficiency versus of the condenser temperature for different working fluids.

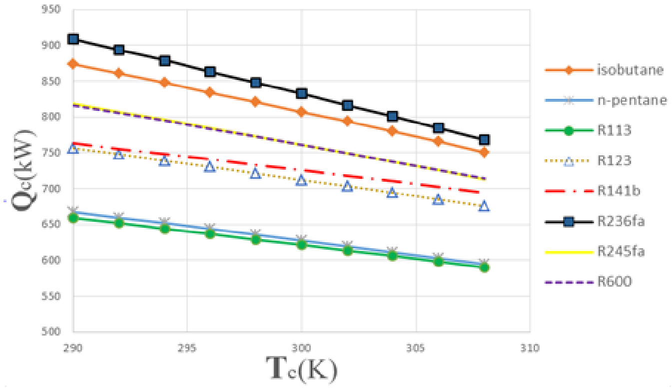

Fig. 7. The variation of the condenser duty versus of the condenser temperature for different working fluids.

Table 8 shows the theoretical optimum values of the evaporator pressure for different working fluid in which will result in minimum loss of condenser duty. The optimum value of the evaporator pressure, using different working fluids, for basic ORC, modified ORC incorporating turbine bleeding, regenerative ORC, and modified ORC incorporating both of them is ranged over (2.967-3.567), (2.967-3.544), (3-3.656), and (2.778-3.033) MPa, respectively. In general, we can say that optimum value of the evaporator pressure for this purpose is ranged from 2.778 to 3.656 MPa for ORCs.

E. Maximization of the net produced power

In addition to reduction of the condenser duty, we can maximize net produced power for specific range of the evaporator pressure in the ORC. However, it is much more complicated to extent this results to the thermal efficiency optimization. Table 9 gives the optimum value of the evaporator pressure for different working fluids based on the net produced power maximization purpose. Even though we have presented the exact values of

Table 8. The theoretical optimum value of the evaporator pressure using different working fluids for the purpose of the condenser duty minimization.

Working fluid	a		b		c		d	
	$(P_e)_{opt}(MPa)$	$(\dot{Q}_c)_{min}(KW)$	$(P_e)_{opt}(MPa)$	$(\dot{Q}_c)_{min}(KW)$	$(P_e)_{opt}(MPa)$	$(\dot{Q}_c)_{min}(KW)$	$(P_e)_{opt}(MPa)$	$(\dot{Q}_c)_{min}(KW)$
R113	3.033	833.4	3.1	740.1	3	711.5	2.778	621.3
R141b	3.478	831.3	3.544	737.9	3.656	708.7	3.033	725.1
n-pentane	3.511	880.1	3.272	748.2	3.37	719	2.778	627.4
R123	3.356	843.4	3.467	747.6	3.478	718.9	2.889	712.3
R245fa	3.389	878.9	3.4	778.9	3.522	755.5	2.833	761.4
R600	3.567	8801	3.511	780.5	3.567	758.1	2.944	760.4
Isobutane	3.389	901.3	3.444	799.4	3.433	780.4	2.778	807.1
R236fa	2.967	916.3	2.967	811.9	3.044	793.4	2.889	839.1

(a): Basic ORC, (b): modified ORC incorporating turbine bleeding, (c): regenerative ORC, and (d): modified ORC incorporating both turbine bleeding and regeneration.

Table 9. The theoretical optimum value of the evaporator pressure using different working fluids for the purpose of the net produced power maximization.

Working fluid	a		b		c		d	
	$(P_e)_{opt}(MPa)$	$(\dot{Q}_c)_{min}(KW)$	$(P_e)_{opt}(MPa)$	$(\dot{Q}_c)_{min}(KW)$	$(P_e)_{opt}(MPa)$	$(\dot{Q}_c)_{min}(KW)$	$(P_e)_{opt}(MPa)$	$(\dot{Q}_c)_{min}(KW)$
R113	2.778	248.4	3	223.6	3	251.8	3.033	256.5
R141b	3.233	250.3	3.467	225.5	3.656	254.5	3.567	258.9
n-pentane	3.2	238.1	3.36	215	3.218	243.3	Unknown	Unknown
R123	3.478	238.8	3.4	215.8	3.478	244.4	3.433	249
R245fa	3.433	203.3	3.4	184.4	3.522	207.8	3.478	212.6
R600	3.6	201	3.622	182.5	3.567	205.2	3.567	209.1
Isobutane	3.478	180.8	3.444	163.9	3.433	182.8	3.389	186.4
R236fa	2.967	166	2.967	151.4	3.044	169.9	3.056	174.5

(a): Basic ORC, (b): modified ORC incorporating turbine bleeding, (c): regenerative ORC, and (d): modified ORC incorporating both turbine bleeding and regeneration.

optimum pressure, but in reality, we recommend to choice any suitable value around its corresponding value for experimental study. Between these recommended optimum values, there are a few couples which have unknown values. This may be able to explain by the fixed values of input parameters which are presented in this paper. The optimum value of the evaporator pressure for having maximum net produced power is ranged over (2.778-3.478), (2.967-3.622), (3-3.656), and (3.033-3.567) MPa for basic ORC, ORC incorporating turbine bleeding, regenerative ORC, and modified ORC incorporating both turbine bleeding and regeneration, respectively. In general, we can say that optimum value of the evaporator pressure for maximizing of the net produced power is ranged from 2.778 to 3.656 MPa in the ORCs, which is as same as the presented limitation for minimization of the condenser duty in subsection D.

Note that we cannot optimize the discussed key parameters by means of the condenser temperature. So, this fact will highlight the importance of the evaporator pressure compared with the condenser temperature. And remember, both of these optimization methods can be used based on their applications.

6. CONCLUSIONS

In this paper, we compared the different appropriate working fluids operation for basic ORC as well as three modified ones. We selected 8 different working fluids (R113, R141b, n-pentane, R123, R245fa, R600, isobutane, R236fa) for this thermodynamics analysis, each of one representing different characteristics. Some of this working fluid such as n-pentane was recommended as an appropriate working fluid for the ORCs, thermodynamically and environmentally. Even though this working fluid is expensive, but it can be a good substitution for a specific purposes. The optimum value of the evaporator pressure was also presented using different working fluids for the purpose of the condenser duty minimization and the net produced power maximization in the organic Rankine cycle. Some of the obtained results can be summarized as follow:

- Between the presented working fluids, R113 and R236fa show the highest and lowest thermal efficiency, respectively.
- The range of thermal efficiency for basic ORC, ORC incorporating turbine bleeding, regenerative ORC, and ORC incorporating both of them are ranged over (15.28-22.96), (15.66-23.21), (17.51-26.05), and (17.98-26.54), respectively.
- Between the investigated working fluids, R113 and R236fa have the highest and lowest net produced power, respectively.
- The ORC incorporating both turbine bleeding and regeneration and basic ORC have the highest and lowest net produced power under the same condition.
- The cooling capacity of the cycles which is stimulated by hot steam is constant for each working fluid.
- Increasing of the evaporator pressure will increase the thermal efficiency of cycle.
- Increasing of the condenser temperature will decrease the thermal efficiency of cycle.
- The optimum value of the evaporator pressure, using different working fluids, for basic ORC, modified ORC incorporating turbine bleeding, regenerative ORC, and modified ORC incorporating both of them is ranged over (2.967-3.567), (2.967-3.544), (3-3.656), and (2.778-3.033) MPa, respectively.
- The optimum value for the pressure of the evaporator is ranged from 2.778 to 3.656 MPa using different working fluids for the purpose of the condenser duty minimization and the net produced power maximization in the organic Rankine cycle.
- Reduction of the condenser temperature will reduce the condenser duty, considerably.

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